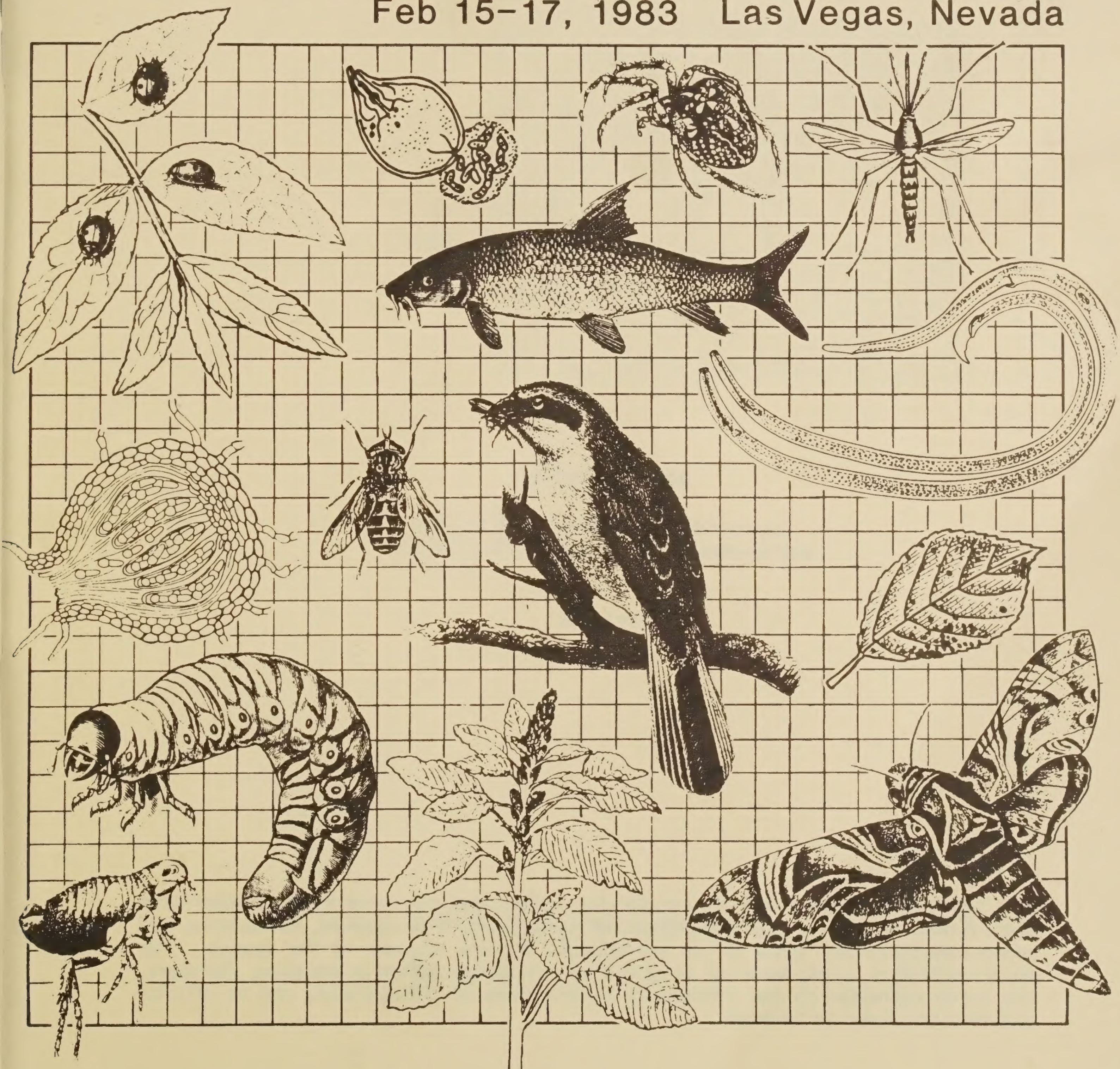
Proceedings of the

National Interdisciplinary Biological Control Conference

Feb 15–17, 1983 Las Vegas, Nevada



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PROCEEDINGS OF THE NATIONAL INTERDISCIPLINARY BIOLOGICAL CONTROL CONFERENCE

February 15-17, 1983
Las Vegas, Nevada

CONFERENCE ORGANIZERS

George E. Allen and Merritt R. Nelson

EDITOR

Susan L. Battenfield

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There are always many people who contribute to the success of an endeavor. The same is true for this unique interdisplinary conference, and we appreciate their efforts.

The dedication of the discussion leaders to putting together a useful document is apparent. Although most were unfamiliar with the nominal group technique (NGT), they were able to use the information from the NGT to write their workshop reports. The section chairpeople are to be congratulated for accepting a task assigned them right before the conference began and working together to draft overviews that tied together the workshops.

We are grateful to the Department of Entomology, Michigan State University, for the use of their word processing unit and staff and their editor, Susan Battenfield, who edited and produced this proceedings. We would also like to recognize the valuable aid given by Pamela L. Love, of the Cooperative State Reasearch Service, who coordinated the scientific and organizational planning for the workshop.

Last, we thank the Cooperative State Research Service, U.S. Department of Agriculture, for recognizing the need for and supporting this first interdisciplinary conference. We commend CSRS/USDA for taking this important first step in bringing disciplines together to discuss a common concern. We hope other agencies, organizations, and groups, whether federal, state, local or private sector, will recognize the value of interdisciplinary conferences, especially for issues like biological control.

Merritt R. Nelson

George E. Allen

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EXECUTIVE SUMMARY

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Having the National Interdisciplinary Biological Control Conference in Las Vegas was perhaps symbolic. Las Vegas means gambling: easy money, lost fortunes, fortunes won at the cast of a die, often the only limiting factor being resources--How much have you got to work with? How far can you stretch them? What "investments" will you make with them? How much return can you get on the investment?

Although the word "gambling" never came up in the meeting (as applied to biological control), the prevailing attitude of the participants was that many researchers in the crop protection disciplines and many administrators feel that biological control is a gamble: maybe it will work, but the element of risk is high, and the outcome uncertain. Nearly all agreed, however, that our ignorance of biological systems increases the risk.

And, the stakes are getting higher. Biological control may be the only alternative in an energy-depleted world where the cost of food production is rapidly reducing the number of people who can afford to pay for the fruits of our labor. Increasing our knowledge of biological control will greatly reduce this risk and open more options for the future. Options was the essence of the National Interdisciplinary Biological Control Conference.

Basically, the conference was the mechanism for bringing together scientists involved in interdisciplinary research and interregional projects in the land grant system. The goal of the conference was to stimulate new thoughts in the approach to research and the use of biological control in crop production by identifying researchable questions and technology needs.

To insure open and full communication between disciplines and to maximize input from all participants, the nominal group technique (NGT) was used in most of the workshops. The nominal group technique is a special-purpose process typically used in small groups focusing on one question. After the discussion leader briefly discusses the scope of the question, each participant writes a list of ideas/answers on a sheet of paper. The ideas then are shared, round-robin, with the group. A recorder writes each idea on a flip-chart in front of the group. Discussion takes place only after all the ideas have been recorded, and discussion is limited to asking for clarification or stating support or non-support of each idea. Members then select a number of priority items (around 7) and rank them. The tally results in a prioritized list of answers.

Most workshops used the nominal group technique and generated lists of ideas in response to their particular question. These lists have been condensed and appended to the proceedings.

When workshops were too large to easily accommodate the nominal group technique, they divided into groups of about twenty and often addressed separate questions. For example, the workshop on "Abundance and Effectiveness" was divided into three groups. Each subgroup addressed different aspects of the question: "What approaches might be used to enhance the abundance and effectiveness of biological control agents?" One group discussed chemical, nutritional, or physical manipulations; another group centered on vegetation and cultural management; and another group addressed propagation and release applications.

Despite the variety of ideas coming from the workshops, many workshops had similar priority needs. For example, identifying and detecting biological control agents was one of the top priority items in 13 out of the 15 workshops. The major concern was the lack of techniques for identifying biological control agents and, as pointed out in the Taxonomy workshop, the need for taxonomic revision of groups that contain biological control organisms. Research is needed to identify traits important in naturally occurring biotypes, ecological differences among biotypes, molecular agents, strains, races, unknown indigenous biological control agents, and crop plants and weeds. Because the biotypes of pests and biological control agents markedly influence the success of a control program, information garnered from such identification would help assure successful biological control programs. Therefore, researchers must understand the diversity existing within target and biological control agent populations. Improvements in identification might

come from regional resource or taxonomy centers, as suggested in the Taxonomy and the Induced and Natural Epidemics workshops. Systematic surveys of insect and plant pathogen populations of interest, including foreign sources and areas of origin, should be conducted, also.

The second greatest overlapping need was to develop a computer-based data management system. Although most workshops had slightly different ideas for such a system, the general idea is that it would be an information center available to all scientists in the crop protection disciplines. Such a center would increase interdisciplinary information exchange and participation of scientists in national programs, and it would probably increase the application of new technology in biological control research. Data stored in the system would include historical information, successful biological control programs, phenological information on all biological control agents, hosts, and targets, and simulation models of host-plant-pathogen systems.

Genetics research and environmental research sometimes went hand-in-hand. As pointed out in the Science of Biological Control overview, with more information on the genetics of successful biological control agents and how the environment affects biological control, scientists could improve biological control agents and explain the deterioration or protect the integrity of biological control agent biotypes. The Biotype workshop directly addressed the issue of genetic improvement of biotypes and preventing deterioration, as did the Molecular Processes workshop, which pointed out that "virtually nothing is known about how insects confer resistance to microbial infection or transmission of pathogenic agents." Several reports called for developing standard genetic techniques and using genetic engineering technology to assist in biological control research.

The need for computer simulations and models interfaced most of the workshops. For example, the Induced and Natural Epidemics workshop stressed the ability to understand environmental factors not only through field observations, but through computer simulations as well. Interpretive models might be developed to assist scientists in looking for success patterns, which would increase our understanding of how best to use biological control.

The more researchers know about biological control, the greater will be the need to evaluate the transition of pest-crop systems from heavy dependence on pesticides to lesser dependence. This point was brought out in the IPM workshop, as was the need for ecosystem analysis and basic life cycle information. Also important are improved sampling techniques—priority needs in the four workshops in the Evaluation and Analysis section.

The Foreign Exploration workshop called for a National Biological Control Organization that would administrate grants, make recommendations, and identify research needs. The organization would collaborate with the OIBC, CIBC, AID, and FAO "to establish an international network for biological control." Such an organization, with its international ties, could also investigate ways to improve the quarantine process, i.e., regulations for introducing and handling candidate species.

Biological control has long been viewed as a subdiscipline within entomology, and, more recently, as a subdiscipline in plant pathology, nematology, and weed science. Reading through the proceedings, it is apparent that biological control can no longer be considered a subdiscipline within a group of disciplines, with each discipline tucking itself into a corner and working on its separate projects. For biological control to succeed, to be a viable alternative for future crop production systems, there cannot be four biological control programs, one under each discipline. Rather, the disciplines must come together, must share their resources, their ideas, and their common principles to make biological control truly interdisciplinary. As a basic discipline it would require the resources, funds, and scientific intellect—only it must be more because it would umbrella all crop protection disciplines.

The conference was a first step toward bringing together the crop protection disciplines to wrestle with real-world problems relative to biological control. As would be normal for any unique undertaking, all was not smooth. Participants had to adjust to foreign jargon and perhaps suspend or realign their definitions. But this was part of the process as the disciplines tossed their concerns and needs for the future of biological control into one common hat. Yet, the

conference was only one step. If no action is taken, interdisciplinary biological control may pull back into a crawler stage.

The overwhelming message running through the conference was that communication and cooperation between the disciplines must continue—they are vital to further successes in biological control programs. Perhaps this is summed up well in the last conference report: Establishing Cooperative Relationships. A group of participants felt strongly enough about the need for continued interdisciplinary cooperation that they submitted a report delineating steps that should be taken to keep interdisciplinary biological control on its feet and moving forward. This report, along with the priority research areas outlined in the workshops, might be the guidelines for taking the next step in cooperative, interdisciplinary biological control.

The next step also may require a broadening of the term interdisciplinary. Throughout the reports and appendices numerous references are made to areas of work that cannot be served within the confines of traditional entomology, plant pathology, and weed science biological control technology. Instead inputs from physiology, biochemistry, molecular biology, genetics, and ecology will be necessary to better understand mechanisms of biological phenomena that are useful in biological control. Increased understanding leads to better application and use. Thus with there inputs, what was an interesting biological phenomena yesterday may be a viable biological control system today. Already genetic engineering techniques are being used to or suggested for improving the effectiveness of microbes and other biological control agents. Such improved agents are beginning to enter the marketplace as products in the era of "biotechnology." Certainly such modified organisms will be some of the early success stories in agricultural biotechnology. It is the application and full use of scientific advances in many biological and physical science disciplines that will insure that biological control technology will rise to meet the needs of crop production in the future.

The conference really consisted of two elements: first, traditional areas of research and concern where ideas were accumulated to improve and expand past successful approaches to biological control and service functions, and, second, ideas that focused on "new" approaches to identifying, understanding, improving and applying biological control agents. Both elements are crucial to future development and success.

We caution readers to keep these ideas in mind as they read the conference proceedings. Remember, too, that there is a redundancy in the reports. This is a strength of the conference, not a weakness. The goal now is to take these ideas a step further: How should they be addressed? With what resources? When?

S. L. Battenfield
M. R. Nelson
G. E. Allen

OPENING REMARKS

ADMINISTRATIVE OVERVIEW

Richard J. Sauer, Director
Minnesota Agricultural Experiment Station
University of Minnesota

The broad objective of this conference is to stimulate new thoughts in the approach to research and application of biological control of pests and diseases in crop production. I would amend and broaden that overall objective to include livestock, as I know there are several here with interests and experience in managing livestock pests.

More specifically, your charge is to (1) set goals and objectives in biological control research and application, (2) evaluate the current state of the science, (3) develop methods of achieving the goals and accomplishing the necessary level of coordination (considerable mechanisms for coordination already exist within the state agricultural experiment station (SAES) system—if properly used), (4) identify researchable questions, providing specific examples, and (5) identify the technology input needs, including the availability of trained personnel to provide those inputs.

I would boil these five objectives down to (1) identify new ideas—research needs, approaches, and priorities, and (2) convince administrators to allocate new resources to biological control research. I urge you to concentrate on the former, while not ignoring the latter. Where you devote efforts to the latter, be creative: research administrators would, or at least should, welcome your creative suggestions.

There are past examples of where similar conferences and workshops, and the resultant proceedings, have identified research priorities and have contributed to successful efforts to obtain new federal appropriations for research in the area(s) being addressed. For example, a Plant Research Imperatives Conference, co-sponsored by Michigan State University and the Kettering Foundation in 1976, helped initiate a USDA Competitive Research Grants Program. The four initial areas of emphasis--photosynthesis, nitrogen fixation, biological stress, and genetic engineering—were identical with those identified at the conference. Similar conferences have occurred in "animal agriculture," soil science, and integrated pest management. They each resulted in a clearer delineation of research needs and priorities, but met with varying levels of success in generating new federal research funding.

How will we secure funding for the new research needs to be identified this week? I must respond to this with a note of realism from my perspective as an experiment station director. During the 1981-83 biennium, which ends June 30, 1983, I will have retrenched $425,000 in state appropriations. In addition, I had to reallocate $325,000 to make up for shortfalls in state funding for increases in faculty and staff salaries and fringe benefits. Thus, I have already used up considerable flexibility and have closed up several lower priority and/or less productive research projects.

Let me also reflect on the federal budget situation. For FY83, which began October 1, 1982, but for which an appropriation was not approved until late December, the SAES's received a 5.7% increase in Hatch, including Regional Research, formula funds. This was barely sufficient to offset the federal share of our faculty and staff salary increases. On McIntire-Stennis (forestry research) funds, we received only a 3.5% increase. This did not cover salary increases and will cause retrenchment over and above the erosion of just the inflationary increases in supplies, expenses, and equipment. The Special Grants item for biological control remained the same as for FY82.

In the FY84 Executive Budget, no increase is proposed for Hatch and McIntire-Stennis. And the biological control special grants item has been eliminated.

With all the above signs, it is easy to become pessimistic about the immediate future for public funding of agricultural research, including that for any new initiatives in biological control. However, despite bud-

get retrenchments and pessimistic short term outlooks, we need to remember the considerable public resources available. For example, despite retrenchments and reallocations in Minnesota, we still have 18 million dollars per year in state appropriations to fund research. This is a considerable resource, and we need to make the best possible use of it.

A problem within the SAES system is that we often lack the flexibility necessary to make redirections and take new initiatives without securing new funds. Long-term commitments to tenured faculty and to the base budgets of departments have tied up the bulk of our funds—sometimes longer than desirable. Not every research initiative requires a 30 year commitment.

If you go home from this conference and approach your Station director for new resources to fund biological control research initiatives, I predict he will say, "Why can't you redirect the resources you now have?"

Granted, we can document that the public underinvests in agricultural research. However, for most directors now to find resources to fund a new project, it means a decision to stop doing something else. In fact, it may mean stop doing two other activities: one to free up funds for retrenchment, the second to fund the new project—and this must be accomplished despite tenure commitments to most of our scientists.

Our traditional manner of managing Station resources, by placing the bulk of them in departmental budgets on a continuing basis, has resulted in strong departments and disciplinary programs. But it has hampered our ability to take <u>inter</u>disciplinary research initiatives when the greatest future potential may lie with funding and facilitating greater <u>inter</u>disciplinary collaboration.

What about private resources? For too long, we in agriculture have not cultivated the considerable potential for gifts and other endowments to build long-term support for our research programs. This is beginning to change, and we have progressed in the last three years at Minnesota, with two endowed faculty chairs and a gift of 2,067 acreas of prime south-Minnesota farmland, half the income from which will fund a Crop Management Center.

What potential exists for generating industry support in the form of grants, contracts, and other agreements? Can the biological control agent be formulated into a proprietary product? Most often, it cannot. However, this is changing with the emerging potential of microbial agents. Perhaps we can pursue arrangements parallel to those in biotechnology, where the private company receives an exclusive license or even patent rights, and we obtain the resources necessary to support continued basic research.

I suggest that you also have a challenge to educate administrators, legislators, and other decision-makers. I identify five educational issues in this regard:

1. Why do we need to pursue any research in biological control, given the apparent abundance of pesticides, plus plant breeding efforts to develop host plant resistance? Why is it important as a pest and disease management tactic? What are the potential benefits?
2. Is there any realistic potential for implementing biological control in other than island or coastal situations?
3. Is biological control an all-or-none tactic, or can it be part of an integrated management program?
4. Can you justify changing the traditional attitude towards biological control, where the greatest potential apparently rested with host-specific parasites, with some isolated successes attributed to predators and insect and plant pathogens being a subject of basic research, but with little practical application? What will you do with the recent developments with subcellular, molecular pathogens and the potential for engineering modifications in these agents?
5. Can you justify the need for funding to support foreign exploration for plant pathogens and entomophagous arthropods?

I applaud the efforts of those who organized this workshop and each of you for contributing your time and effort to participate. I hope the conference will be productive. I am committed to doing whatever I can, as one administrator, to assure that your recommendations will receive attention and consideration.

KEYNOTE SPEAKERS

WHERE WE ARE AND WHAT WE NEED TO DO IN BIOLOGICAL CONTROL:

THE ENTOMOLOGIST'S VIEW

Carl B. Huffaker
Division of Biological Control
University of California, Berkeley

WHERE WE ARE

In order to talk about where we are and what we need in biological control we must establish the limits of who we are—that is, what, properly, do we do. With no offense to those who may think differently, the discipline for many years, as represented by the leadership and programs of such people as W. R. Thompson of the Commonwealth Institute of Biological Control, H. S. Smith of California, Phillipe Sylvestri of Italy, R. C. L. Perkins of Hawaii, R. J. Tillyard and A. P. Dodd of Australia, and G. C. Ullyett of South Africa, has defined biological control as the suppression of a host of prey species by its parasites, predators, and pathogens—its natural enemies.

The premise on which biological control rests is that in certain circumstances many populations are held at low densities by their natural enemies (i.e., parasitoids, predators, pathogens, and other such forms known as "antagonists" that biologically control plant pathogens). For many species that are pests or potential pests of crops, these enemies provide ample crop protection. This premise is one aspect of the "balance of nature," which implies that populations are restricted in numbers and that with an increase in density they use up resources, defile their habitat or abodes, or generate increased intensity of inimical factors, such as predators, parasites, pathogens, or antagonists.

These enemies thus have a unique role, in that a host's regulation by its natural enemies arises as a natural enemy-host population interaction. Action of hormones or pheromones, or sterile or genetically deranged insects of the pest species itself, is not at all the same, neither is the development of resistant crop or animal varieties, valuable as these methods often are. So the discipline, by its unique nature and by tradition, is confined to action of parasites, predators, pathogens, and "antagonists."

Classical biological control tries to establish, in a new area, a biological control link existing in the native home area, or one related to it. Observed rarity of a pest species in its native home and devastating status in an invaded area lacking effective natural enemies suggests the possibility that control might be achieved by introducing its associated enemies. This theory follows the general thesis of the roles of natural enemies in the balance of nature; it does not explain how they achieve or maintain such a role.

The role of predators and parasitoids in the biological control of insects was spectacularly demonstrated by introducing *Rodolia cardinalis* into California in 1888 to control cottony cushion scale. The control of this pest in California has remained virtually complete to this day, despite the heavy use of insecticides. Following this success, a worldwide traffic in biological control agents developed for use against insects and weeds. Classical biological control has resulted in 140 or more substantial or complete successes with insect pest species and some 40 cases with weeds. We are now learning the possibilities for plant disease control. Recently, a tiny beetle, *Cyrtobogous salvinia*, cleared Lake Moondara in Australia of the pest aquatic fern, *Salvinia molesta* (Room et al. 1981).

Introducing a complex of enemies is often more effective than the "best" one alone. In Canada, the complex of two parasitoids and a *Borrelina* virus keep the European spruce sawfly at very low endemic densities. The outbreak was brought down initially by the virus, with subsequent control mostly from the parasitoids, *Drino bohemica* and *Exenterus* sp. However, it seems that the parasites may spread the virus at a host density too low to generate virus maintenance and full effectiveness without the parasites (Clausen 1978). Another example where two natural enemies are more effec-

tive than the "best" one alone is the control of parlatoria scale in California by *Aphytis paramaculicornis* and *Coccophagoides utilis*. Phenomenal control is maintained by these two species even though the most efficient one, *A. paramaculicornis*, is not always satisfactory alone, and *C. utilis* alone fails entirely.

Different sibling species or different ecotypes of a species may exist over a broad heterogeneous distribution area, and each sibling or ecotype is adapted to the abiotic and biotic conditions of its area. Thus, introducing a natural enemy complex throughout such regions may better satisfy the needs for all of the pest-infested areas. The literature contains examples where a parasitoid introduced in one area failed, but the same, or a sibling, species, when introduced into a different climatic ecotype, produced good biological control. Other examples are in Australia *Trissolcus basalis* against *Nezara viridula*; in British Columbia, *Bigonocheta spinipennis* against *Forficula auricularis*; and in California, *Aphytis* against *Parlatoria*, and *Trioxys pallidus* against *Chromaphis juglandicula* (Clausen 1978). This also accounts for the need for solid and continuing support for taxonomy.

The total activity or numbers of resident natural enemies may be increased through manipulations that raise their numbers or improve their performance, as with augmentative releases, use of kairomones, or of habitat improvements that conserve them, or increase their on-site efficiency and/or reproduction.

In cotton in China and in tobacco in North Carolina, caterpillars are controlled by putting colonies and/or nesting sites of wasps in the fields. In Europe nest boxes for insectivorous birds are placed in the forests. Percent parasitism of *Heliothis* eggs by *Trichogramma* has been increased by spraying host kairomone material on cotton leaves in Georgia. Presumably, Ken Hagen and others who are here can elaborate on this and related advances in behavioral technology (Nordlund et al. 1981).

The outstanding *Trichogramma* release programs in China have recently been invigorated by the large-scale rearing of *Trichogramma* in "artificial host eggs." The artificial host medium, either a pure, chemically defined diet or one incorporating, among other things, chicken eggs, is encapsulated in a wax-plastic covering and the "eggs" are blown out from an aspirator-type machine and caught in a gauze apron. Perhaps Dr. Li Li-Ying will describe this work herself, as she is here.

Also, perhaps an annual spring release of natural enemies that cannot overwinter in a given area would be beneficial. A current success is *Pediobius epilachnae*, which is released each spring to control the Mexican bean beetle in our southern states.

The impact of parasitoids and predators thus has been broadly demonstrated for alien pests. But indigenous parasitoids and predators are perhaps equally significant in controlling indigenous potential pests. For example, DDT, when used on citrus, eliminated *Rodolia*, which resulted in tremendous outbreaks of cottony cushion scale. DDT and other pesticides have so interfered with various natural enemies that alien and indigenous species that had been of little concern often had explosive outbreaks. Such naturally occurring biological control exists all around us—without it, our pest problems would be much worse. Thus, pesticides eliminated the natural controls and created many "induced pests" (DeBach 1974).

Integrated control is often concerned with correcting these induced pest problems using pesticide-resistant strains. Examples of induced pests have been seen in the build-up of tetranychid mites throughout the world, bollworms and budworms in cotton, bagworms in Malaysia, cyclamen mites in strawberries, and many others. The notorious recent example is the tobacco budworm in Texas, Mexico, and California.

The recent program of Marjorie Hoy in developing strains of the predatory mite, *Metaseuilus occidentalis*, resistant to certain organophosphorus, carbamate, pyrethroid, and sulfur pesticides, suggests what might be done to genetically improve other natural enemies—if adequate effort is put into it.

Similar problems have occurred in glasshouse plantings. Mites in greenhouses in England early developed resistance to acaricides. This led H. N. Hussey to explore possibilities of controlling them with predatory mites. The greenhouse whitefly was known to be heavily parasitized by *Encarsia*. The aphid *Myzus persicae*, a major pest, was also sometimes effectively parasitized. Careful attention to the biologies of the hosts and the growth characteristics of the

crops and of the natural enemy culture and release procedures, as well as the glasshouse temperature, gradually led to methods by which each of these pests can be controlled mostly via natural enemy releases, with minimal and carefully ordered use of chemicals for other pests. The method has been adapted and used in many countries.

A short season IPM cotton production system has been developed in South Texas that avoids prolonged exposure of the crop to boll weevils and allows early harvest, which reduces overwintering boll weevils. This system is combined with chemical "diapause treatments" for weevils destined to overwinter. The weevil population is then slow to develop the next season; hence, summer treatments can be delayed so that natural enemies of *Heliothis* spp. can control those pests.

Releases of the pest itself, to carry a natural enemy over a period of host absence or to pre-establish the natural enemy at an early time of crop development, have been tested. C. E. Kennett and I demonstrated this method's potential for cyclamen mite control on strawberries, but the method was not adopted. Likewise, Frank Parker and associates (Huffaker et al. 1976) obtained good field control of *Pieris rapae* in Missouri by releasing small numbers of the butterflies during a critical period, combined with releases of *Trichogramma* and *Apanteles rubecula*. Again, the method was not adopted.

In China, however, this procedure is used in purple lac culture. The parasitoid *Bracon greeni* is released to control the moth caterpillar, *Eublema amabilis*. But there is a season when the parasitoid population has too few hosts to sustain itself, so small numbers of the pest moth are colonized to bridge the gap. Integrated pest management (IPM) as used in glasshouses where the pest is introduced first is another example of where a beneficial pest-natural enemy interaction is established by introducing the pest.

Substantial progress has been made in discovering and developing a strain of *Bacillus thuringiensis* to control mosquitoes and blackflies. Also, common guppies can be added to *Gambusia affinis* to control mosquitoes in rice (demonstrated in New Guinea).

It is upon this solid empirical base that applied biological control of arthropods rests. At every stage in its development, funds to support it and enthusiasm to pursue it have derived from some new, surprising, or outstanding practical success. These successes are largely empirical because no explicit insights into the detailed ecological behavior of the agents to be introduced formed the basis for making the introductions. The same can be said regarding the native natural enemies presumed to have been keeping innocuous potential pests at low levels before the pesticide-induced outbreaks.

The theory of biological control, a practical economic concept, goes well beyond most abstract theories of predator-prey (including host-parasite) interactions, as if such interactions occur without intrusions from factors external to the interaction. Yet, such theoretical studies on the possibilities inherent to the interaction can furnish certain insights.

The principal attributes of a good arthropod natural enemy are summarized as follows:

> fitness and adaptability, searching capacity, power of increase relative to that of the host (prey), host specificity and host preference, synchronization with the host and its habitat, density-dependent performance relative to either or both the host's density and its own density, detection and responsiveness to the condition of the host, and competitive ability (Huffaker 1971).

The numerical response of a natural enemy in the field, as well as the functional response, to increase in prey density is most important and depends on two primary attributes—climatic adaptation and lifetime searching capacity. Theoretically, rate of increase in female progeny/female parent, generation to generation, as related to host density, furnishes a measure of this numerical response; the functional response is a main contributant. The parasitoid having the steeper numerical response in nature in the lower ranges of host density would be expected to be the best natural enemy.

Mostly, such population modeling has involved a set of paired equations: one for the prey (or host), and one for the predator (or parasitoid). Only the predator population is resource (prey) limited; the prey is limited by its predator (or parasitoid) in a reciprocal interaction. Some early (Volterra 1927) and some later (May 1981) modeling has also

employed a logistic-type of density-dependent resource restriction on the prey population, and other efforts have concentrated on density-dependent stabilizing behavior for the predators or parasitoids (Gutierrez and Baumgaertner 1983). The models, however, have still been based on the Lotka-Volterra or Nicholson-Bailey basic formulations.

It is of much interest that now a new approach to modeling host-parasite and predator-prey interactions—a method more appropriate to field populations—has been explored by A. P. Gutierrez, Wayne Getz, and associates at Berkeley. This method assumes that predator or parasitoid population growth has a density-dependent response to the resource (prey) available per capita predator population. This per capita resource availability is, basically, the same as the supply/-demand ratio used by Gutierrez and Baumgaertner (Hassell 1978) to incorporate physiology and behavior into their predator-prey models. Predator demand depends on the size of an organism, its age, and its level of hunger, which may be a function of the number of day-degrees that have elapsed since its last meal, and on various other physiological parameters. The value of this approach is that it verifies growth concepts at all trophic levels, and it allows multiple trophic level models to be put together consistently.

In conclusion, I believe that classical introductions of natural enemies will remain useful. Yet, more attention to modern taxonomic methods for identifying sibling species and strains, better climatic fits, and characteristics likely to be beneficial should produce worthwhile rewards. We need to develop more ways to use native natural enemies. We also must protect the uniqueness of our discipline from the lumpers who wish to include as biological control all biological forms of pest control. Biological control and pest resistant varieties are the central feature of most IPM programs, with these methods and cultural methods integrated closely with limited chemical use.

I hope these brief comments will adequately introduce the area of this symposium. I would add that as biological control advances, or as integrated control advances, so will the other. But they should not be equated.

WHAT WE NEED TO DO

A. Firmly establish and maintain the limits of our discipline, as referred to above, as our uniqueness.
B. Seek administrative, organizational, and societal arrangements to foster the recognition of biological control as an entity across taxonomic categories and conventional administrative lines.
C. Seek support for vigorous programs of research in both basic and applied areas:
   1. Taxonomic work
   2. Introductions (including new biotypes)
   3. Genetic improvement
   4. Augmentation
   5. Conservation
   6. Evaluation technology
   7. Implementing biological control in real IPM systems (crops or medical and veterinary areas).

I hope this conference can address itself to these questions concerning the future of biological control.

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STATE OF THE ART: PLANT DISEASES
(with an addendum on weed control)

Ralph Baker
Botany and Plant Pathology Department
Colorado State University

Although biological control of plant pathogens has been studied for many years, I will discuss only a few of the systems where the mechanisms of biological control have been elucidated (see Baker and Cook 1974, Baker and Snyder 1965, and Papavizas 1981 for books that discuss biological control of plant pathogens). Not only will this provide insight into the current strategies in using and enhancing biological control agents, but it will also illustrate the complexity of the systems currently being developed in plant pathology.

The organizers of this meeting defined biological control as pest suppression with biotic agents, excluding the process of breeding for resistance to pests, sterility techniques, and chemicals modifying pest behavior. Figure 1 illustrates the concept.

MECHANISMS

The mechanisms involved in biological control generally are grouped into two categories: antagonism and cross protection (Figure 1). Antagonism is the direct damage a biological control agent inflicts on a pathogen by antibiotic substances, competition, or exploitation. Cross protection, used here in the broad sense, is where plant host tissues containing a biological control agent are protected from a subsequently introduced pathogen.

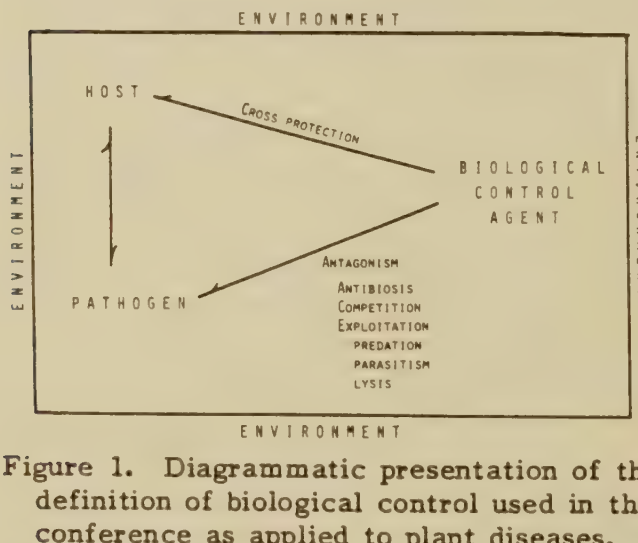

Figure 1. Diagrammatic presentation of the definition of biological control used in this conference as applied to plant diseases. A Biological control agent may antagonize the pathogen directly or operate within the host tissue itself in cross protection. Environment is often manipulated to enhance the activities of the agent.

Examples of these various mechanisms are given below. Since clear-cut evidence for substantial biological control through antagonism due to antibiosis (external to the host) has not been demonstrated, this study area will not be treated.

As in any attempt to categorize biological phenomena, mechanisms overlap and more than one may operate in a system. For example, the cross protection, resulting from introducing an avirulent strain of the crown gall pathogen, has been ascribed to the production of an antibiotic. This suggests an antibiosis mechanism; however, recent experimentation (Cooksey and Moore 1982) suggests that avirulent strains without the antibiotic can reduce the size of galls.

Competition

The term is used here in the narrower sense of "active demand in excess of immediate supply of material or condition on the part of two or more organisms" (Clark 1963). Microorganisms compete almost exclusively for substrate (Baker 1981). An example has recently been furnished in connection with soils suppressive to the Fusarium wilt pathogens (Scher and Baker 1983).

A Metz fine sandy loam soil, found in the Salinas Valley of California, suppresses Fusarium wilt diseases (Smith and Snyder 1971, 1972). The factor inducing suppressiveness is transferable; that is, only 600g/m^2 of suppressive soil added to conducive (steamed) soil in a commercial greenhouse decreased disease 60% over two years (Baker 1981, Scher and Baker 1980; Figure 2). Others have

reported similar phenomena (Albouvette et al. 1980, McCain et al. 1980). Obviously a biological, rather than a physical, factor, capable of multiplication, induced suppressiveness. Physical factors, such as pH, do not multiply.

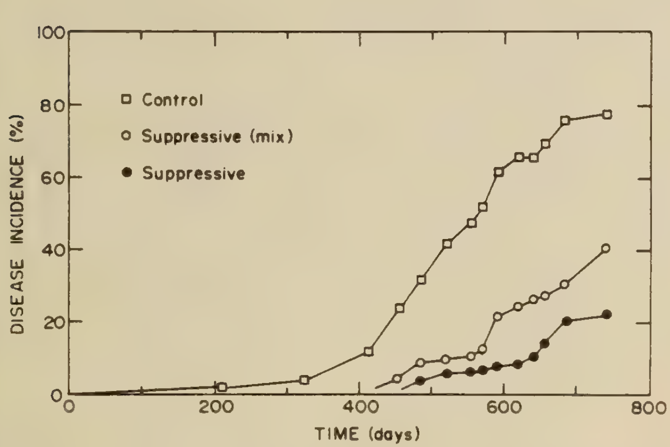

Figure 2. Incidence of Fusarium wilt of carnations in steamed ground beds in a commercial greenhouse. Suppressive (mix) involved mixing Metz fine sandy loam (suppressive) into autoclaved Fort Collins clay loam (1:99 w/w) and incubating for 1 mo. This incubated mix was added in the ground bed at time of transplanting at $600 g/m^2$. In the suppressive treatment, nondiluted Metz fine sandy loam was added to plots at the same rate. No soil was added to the controls (from Scher and Baker 1980).

Subsequently, a fluorescent pseudomonad (identified as *Pseudomonas putida* (Trevisan) Migula) isolated from the Metz fine sandy loam, induced suppressiveness when added at 10^5 cells/g conducive soil (Scher and Baker 1980, Figure 3). Fluorescent pseudomonads produce iron-acquiring compounds, called siderophores (Neilands 1974, Teintze et al. 1980), that compete for iron (Fe) when this element is in low supply. Kloepper et al. (1980) suggested that soils suppressing Fusarium wilt and take-all pathogens contain siderophore-producing microorganisms that complex Fe. Thus, it is less available to soilborne pathogens incapable of producing comparable Fe-transport agents.

Scher and Baker (1983) expanded this theory. Previously, only carbon and nitrogen were thought to be essential for soil-borne pathogens to germinate and penetrate infection courts (Baker 1968). Scher and Baker (1983), however, demonstrated that the Fusarium wilt pathogens needed Fe to complete propagule germination. These pathogens produce siderophores--the hydroximate class with a stability constant (a measure of Fe-binding ability) of $\log_{10} = 28$ (Emery 1965). Thus, any chelating agent with a stability constant of higher value compete successfully for Fe when that element is in short supply. Indeed, a commercially available Fe chelating agent, ethylenediaminedi-0-hydroxyphenylacetic acid (EDDHA), also induced suppressiveness when added to (previously) conducive soil (Figure 4).

The theoretical basis for suppressiveness to soilborne organisms through competition for Fe (Scher and Baker 1983) involves the interaction of numerous biological and physical/chemical factors (Figure 5). The Fe available for plant or microorganism growth is defined by the equilibrium reaction:

$$Fe(OH)_3 + H^+ \rightleftharpoons Fe^{3+} + 3\ H_2O$$

The principal factor mediating the equilibrium of this equation is the pH of the soil: the more alkaline the soil, the less Fe^{3+}

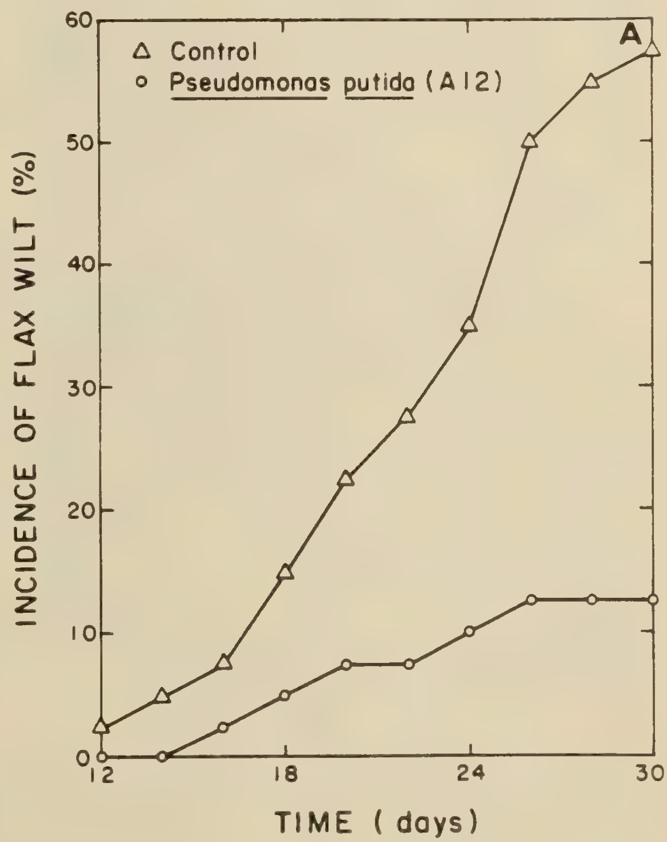

Figure 3. Effect of addition of cells of *Pseudomonas putida* to conducive soil on incidence of flax wilt (from Scher and Baker 1983).

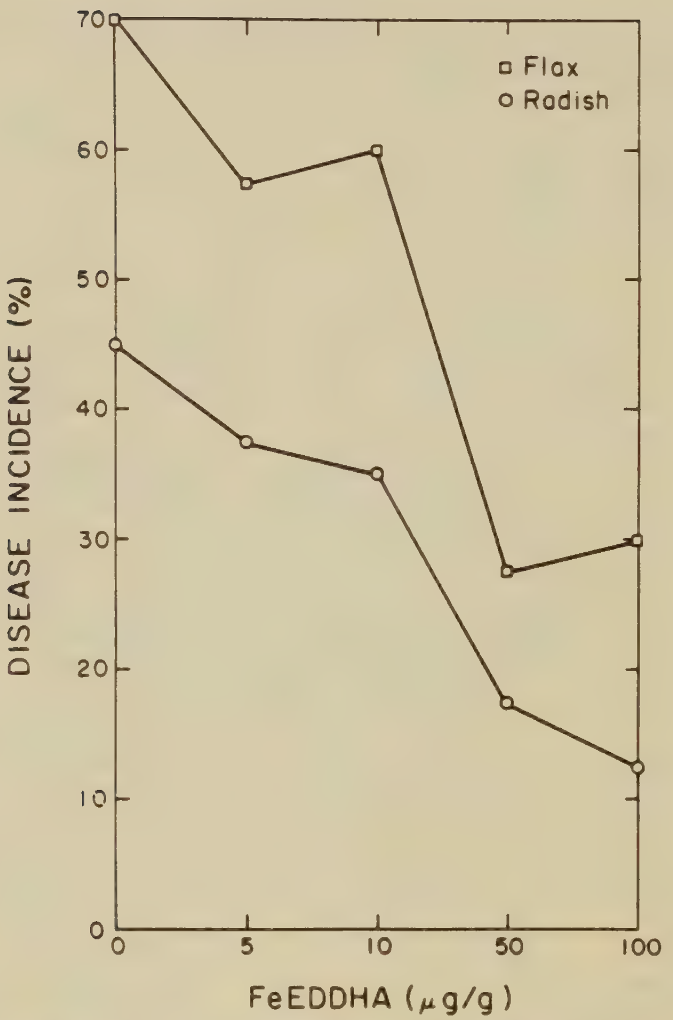

Figure 4. Mean incidence of Fusarium wilt when FeEDDHA was introduced into conducive soil infested with *Fusarium oxysporum* f. sp. *lini* or f. sp. *conglutinans* (from Scher and Baker 1983).

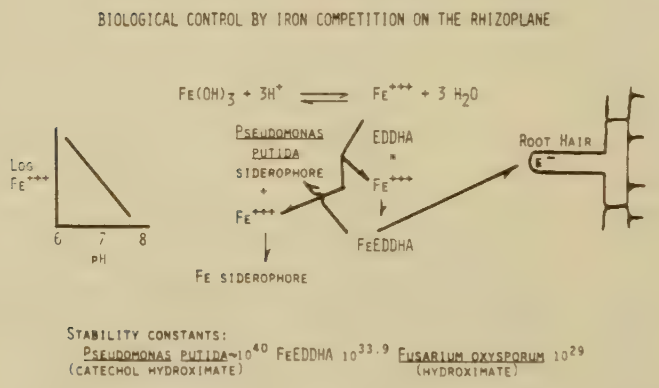

Figure 5. Mechanisms and pathways involved in soil suppressive to the Fusarium wilt pathogens through competition for iron (Fe).

is available. The influence of soil pH, therefore, may be considerable in determining whether Fe^{3+} can be rendered unavailable for the pathogen and, ultimately, whether a soil is suppressive or conducive. This may explain why the Metz fine sandy loam (virginal pH of 8.1) loses much of its suppressiveness when the pH is adjusted to 7.0 and is conducive at pH 6.0 (Scher and Baker 1980).

The siderophore produced by *P. putida* is of the catecholhydroximate class and has a stability constant many powers of 10 greater than the hydroximate siderophore of the Fusarium wilt pathogens (Teintze et al. 1980). Thus, when the rhizosphere-competent *P. putida* colonizes the infection court (root tip), it competes successfully for the available Fe.

Conduciveness in previously suppressive soils was induced by adding the Fe chelator ligands ethylenediaminetetraacetic acid (EDTA) or diethylenediaminetetraacetic acid (DTPA); whereas FeEDDHA enhanced suppressiveness (Scher and Baker 1983). These ligands bind Fe^{3+} at various stability constants: EDDHA, $\log_{10} K = 33.9 >$ DTPA, $\log_{10} K = 27.3 >$ EDTA, $\log_{10} K = 25$ (Lindsay 1974). Therefore, those ligands, with stability constant values less than the siderophore of the pathogen, induced conduciveness; EDDHA, with a stability constant higher than the pathogen's, induced suppressiveness.

This is a dynamic system where the siderophores, produced by the pseudomonads, the EDDHA, and the root of the host, combine to render Fe^{3+} limiting for pathogenesis by the Fusarium wilt pathogen.

Exploitation

Mites and vampire amoebae prey on the thalli of fungi in soil (Homma et al. 1979); however, evidence so far suggests that these antagonists do not substantially impact biological control. In contrast, a number of pathogens are biologically controlled by hyperparasitism. A system in which suppressiveness to *Rhizoctonia solani* Kuhn through monoculture illustrates this mechanism (Henis et al. 1978a, 1978b, 1979, Wijetunga and Baker 1979).

Suppressiveness, induced through monoculture of a susceptible crop, has been reported (Baker and Cook 1974). The classic case is take-all decline where repeated plantings of wheat over a seven to eight year period induced suppressiveness (Shipton

1977). The mechanism appears to be the selective enhancement of population density and activity (Baker and Chet 1982) of fluorescent pseudomonads (Weller and Cook 1981a, 1981b). However, monoculture of radishes planted at weekly intervals induced suppressiveness to *R. solani* in five weeks or less (Henis et al. 1978a, Wijetunga and Baker 1979). During this period, *Trichoderma* spp. increased from a non-detectable level to approximately 10^6 propagules/g of soil (Liu and Baker 1980). Adding this concentration of laboratory-produced conidia of the *Trichoderma* induced suppressiveness in previously conducive soils. Suppressiveness was influenced (predictably) by temperature (Harman et al. 1981) and soil pH (Chet and Baker 1980, Chet and Baker 1981), which illustrates the importance of environmental factors on the activity of biological control agents.

Trichoderma spp. are well-known mycoparasites. Typically, their hyphae are attracted to and coil around the thalli of fungi; eventually the cells of the fungal host disintegrate (Chet et al. 1981, Figure 6). Such hyperparasitism during monoculture of a susceptible host may reduce the inoculum density of the pathogen—to undetectable levels for *R. solani* (Liu and Baker 1980).

Trichoderma spp. and other potential fungal antagonists cannot tolerate many fungicides, such as the benzamidazoles, routinely used as chemical control agents. Integrated control by chemicals and biological control agents, therefore, is not only impractical, but such fungicides may decrease the activity of the agents. In studies using induced mutations, *Trichoderma* spp. became tolerant to the benzamidazoles (Chang et al. 1983, Papavizas and Lewis 1981). This increased the potential for integrated control and provided an agent that could be "tagged." Then the antagonist could be introduced into the soil and its population density followed through dilution plate techniques with selective media containing the benzamidazole.

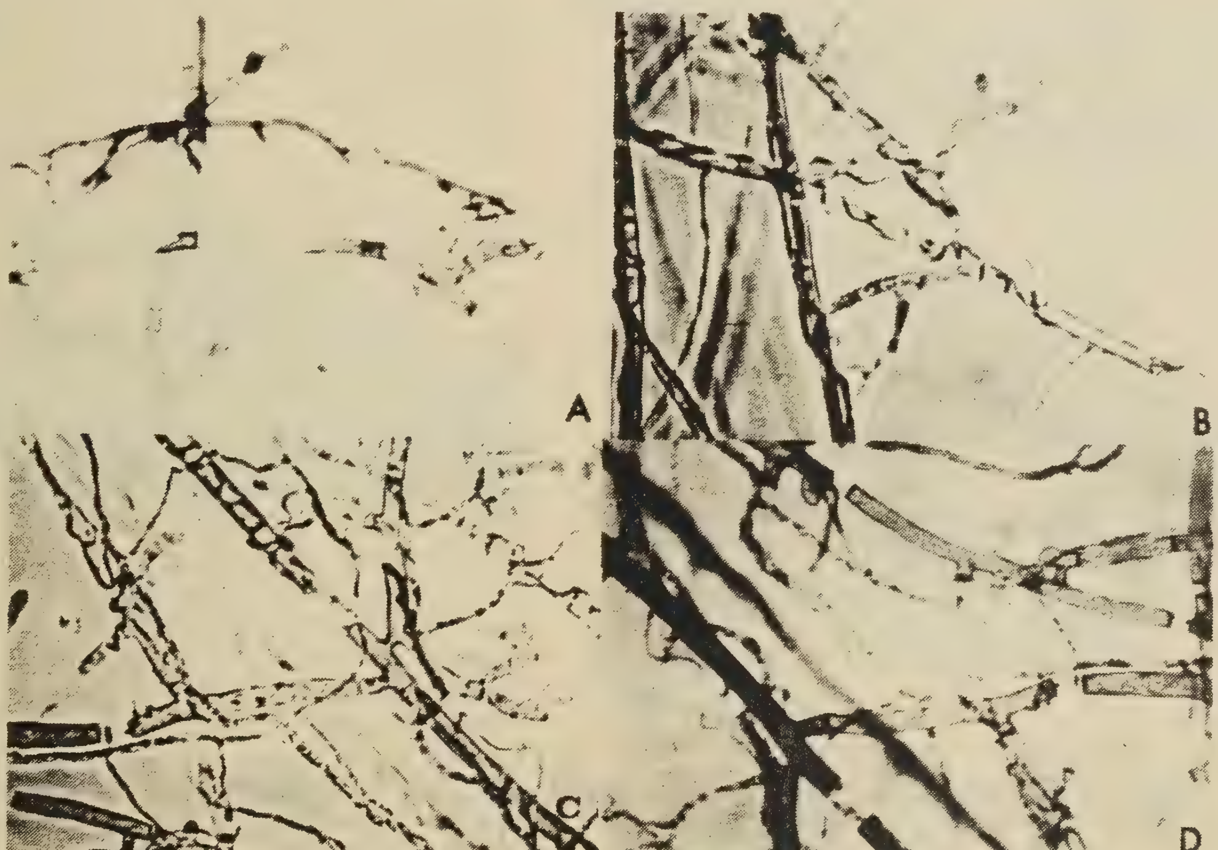

Figure 6. Interaction between *Rhizoctonia solani* (larger hyphae) and *Trichoderma harianum* (smaller hyphae) *in vitro*. A, B, contact and coiling of hyphae of *T. harzianum* around thallus of *R. solani*. C, D, Lysis and separation of hyphae of *R. solani* at later state of interaction (from Liu and Baker 1980).

Such mutants were not only as effective in biological control as the wild type, but sometimes performed more efficiently.

For example, *Sporodesmium sclerotivorum*, a mycoparasite of sclerotia of the lettuce drop pathogen, reduced incidence of the disease in three successive crops (Ayers and Adams 1981). Lysis of the thalli of fungi attributable to either auto-or heterolysis potentially could be used for biological control (Baker 1968), but interest in this mechanism has only recently been revived. Figure 7 illustrates lysis *in vivo* in the rhizosphere of a root and a successful attempt to duplicate the phenomenon *in vitro*.

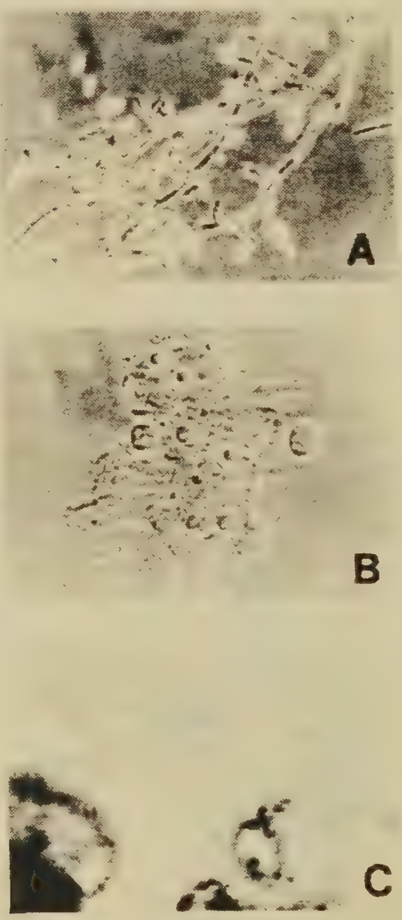

Figure 7. Lysis of hyphae of *Fusarium oxysporum* f. sp. *conglutinans*. A, Thallus not lysed; B, lysis *in vitro* by bacteria; C, lysis in rhizosphere of radish growing in suppressive soil (by permission, B. Sneh).

Cross Protection

Kuc (1982) reviewed the mechanisms associated with resistance to viral, bacterial, and fungal diseases induced by introducing an avirulent or nonpathogen. A biological control agent typically is "inoculated" into a plant host. The plant recognizes the presence of a microorganism foreign to its constitution. This signal induces a resistance reaction either as a chemical or a morphological response. Subsequent introduction of a virulent pathogen finds the host "forewarned" and its resistance increased.

An example is a system where *Fusarium roseum* (LK.) emend Snyd. & Hans. ordinarily induces a stem rot of carnations (Baker et al. 1978). The pathogen enters through wounds occurring when cuttings are taken for propagation from mother plants. Conidia of the pathogen readily germinate and infect the wounded tissue (Figure 8A). When a nonpathogenic isolate of the isolate of *F. roseum* (or many other fungi) (Figure 8C) is placed on the wound, however, the conidia of the pathogen do not germinate (Figure 8B). The nonpathogen, in this case, triggers a response where the host produces a potent antifungal agent.

One of the few registered biological control agents currently in use is an avirulent strain of the crown gall pathogen. The bacterial agent, introduced on seeds or seedlings, protects against subsequent invasion by the pathogen. An antibiotic, agrocin, produced by the biological control agent, has been implicated in the mechanism, although strains not producing agrocin may also reduce gall size (Cooksey and Moore 1982, Moore 1981, Vidaver 1981). Also, in certain geographical regions, the agent has proved ineffective in control.

A transmissible trait inducing decreased virulence has been implicated in the biological control of *Endothia parasitica* (Murr.) Anderson & Anderson (MacDonald et al. 1978). This phenomenon is called hypovirulence. When an avirulent strain of appropriate compatibility is introduced into chestnut trees, hyphal anotomoses occur with the virulent pathogen. A double-stranded RNA (a mycovirus) is probably the transmissible factor, although virulent strains containing the mycovirus also have been found. Cross protection by this mechanism was first observed in Italy, but has since been reported in many locations in the world, including the U.S.

DELIVERY SYSTEMS

As mentioned above, *Trichoderma* spp. may be mixed into soil to induce suppressiveness (Baker and Chet 1982). However, the amount of the material required in field application is often prohibitive. Even so, *T. harzianum* Rifai has been incorporated into pellets containing molasses and was success-

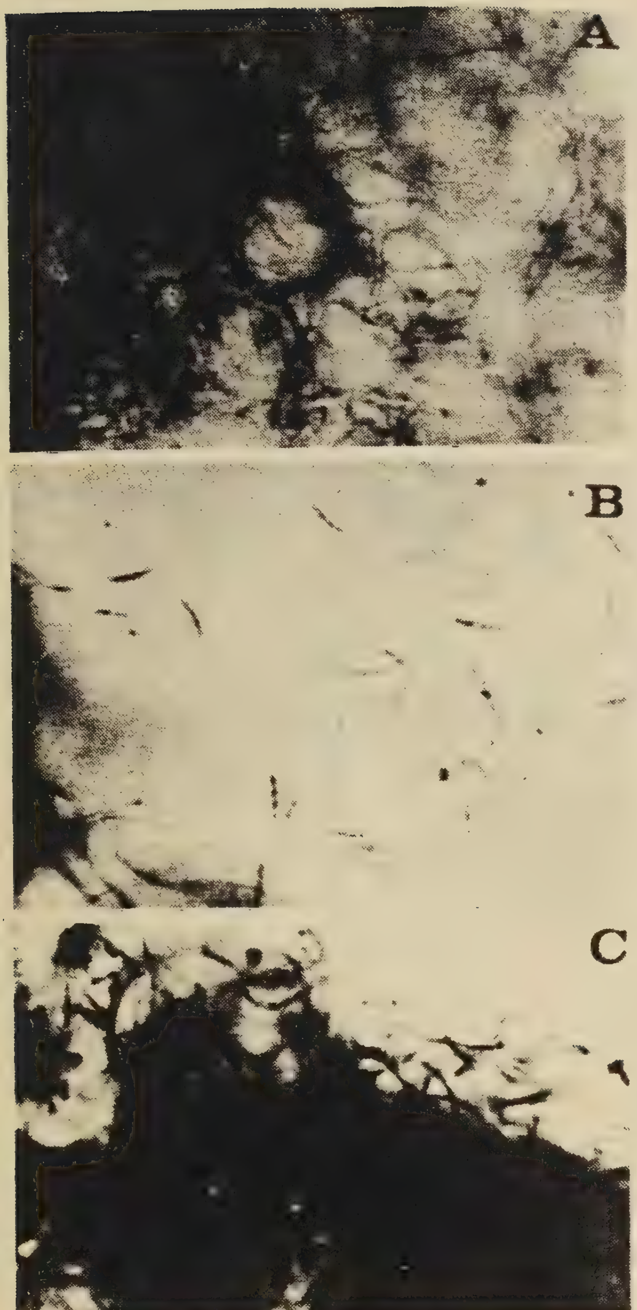

Figure 8. Germination of conidia of *Fusarium roseum* in the infection court of cut carnation stems 24 hr after wounding. A, Conidia germinating in infection court in the absence of biological control agent (nonpathogenic *F. roseum*). Walls of host parenchyma may be seen in the background. B, Nongerminated conidia of the pathogen in the infection court infested with the nonpathogen. The dark areas in the background are portions of the mycelial mat of the biological control agent. C, Mycelial mat of nonpathogen in the infection court without addition of conidia of the pathogen (from Baker et al. 1978).

ful in controlling Southern blight of peanuts (Backman and Rodriguez-Kabana 1975).

Since soilborne organisms may induce pre- and/or post-emergence damping-off, applying agents to seeds is an attractive delivery system (Figure 9). Seed treatment has been particularly effective in greenhouse tests (Harman et al. 1980, Harman et al. 1981); however, some success has been realized in the field (Kommedahl and Windels 1981).

Some bacteria, particularly pseudomonads, are rhizosphere competent (Schmidt 1979); that is, they have short generation

Figure 9. A, Spores of *Trichoderma harzianum* on treated radish seed before germination. B, Hyphae and spores of *T. harzianum* on radish seed coat after 2 days of incubation in a moist chamber. In both photographs the bar on the lower left corner represents 10 μm (from Harman et al. 1981).

periods and can colonize and grow with a developing root as it penetrates the soil. This attribute has been exploited by treating wheat seed with pseudomonads to biologically control take-all of wheat (Weller and Cook 1981b).

AN ADDED FEATURE—INCREASED GROWTH RESPONSE

Schroth and his research group at the University of California (Berkeley) applied pseudomonads to seeds or planting material and noticed a significant and sometimes spectacular increase in growth (Schroth and Hancock 1982). The mechanisms may inhibit the activity of debilitating plant pathogens, which induce no obvious symptoms other than stunting nontreated plants (Figure 10). Thus, biological control agents have the potential for controlling conventional plant pathogens and increasing growth, which often more than pays for the cost of application.

Currently, this scenario is most appropriate for ornamental greenhouse culture. In such systems, soil mixes are routinely used, which are appropriate for applying biological control agents. These mixes are often treated with steam or fumigants, which insure a rich medium for reinfestation and occupation of ecological niches by the agents. Further, in contrast to field conditions, environmental factors such as temperature, soil pH, and water relations are usually conducive to introduced antagonists. Mutants, tolerant to commonly used fungicides, may be employed so that control is integrated. Finally, the increased growth response insures not only cost effectiveness but additional profits.

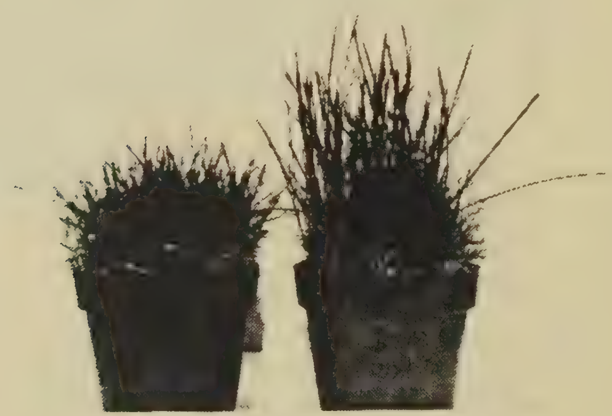

Figure 10. Increased growth response in plugs of turf set in pots not infested (left) or infested with *Trichoderma harzianum* (by permission, C. Rassmussen-Dykes).

This potential has recently been realized (Chang et al. 1983). Conidia of *T. harzianum* applied in the rooting hormone to carnation cuttings gave approximately 50% control of *Rhizoctonia* stem rot. A benzamidazole, applied at the same time, gave similar control. Subsequent introduction of *T. harzianum* to the rooting medium or potting mix substantially increased the weight of plants and the number of breaks and flowers in chrysanthemums and petunias.

This overview has emphasized the positive potentials for biological control of plant pathogens. Numerous problems in identifying, detecting, enhancing, and applying biological control agents still remain. The efficient use of such agents in field application has yet to be realized. However, knowing the mechanisms and associated ecological restraints will add to the efficient use of these agents.

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ADDENDUM:

BIOLOGICAL CONTROL OF WEEDS WITH PLANT PATHOGENS

R. Charudattan
Plant Pathology Department
University of Florida

Although the idea of using plant pathogens to control weeds is not new and some successful attempts were made before the sixties (Wilson 1969), only in the last decade has there been a resurgence of interest in this area. This interest is increasing as evidenced by the numerous new projects (Templeton 1982) and the recent registration of two mycoherbicides for commercial use. A review of the theoretical and empirical knowledge on this subject has been recently published (Charudattan and Walker 1982). Currently, two strategies of biological control of weeds with plant pathogens are recognized: the classical and the microbial herbicide (Templeton 1982). In the classical strategy, a pathogen from the native habitat of an introduced weed is released into an adventive range of the weed; under suitable conditions an epidemic ensues. With a severe epidemic, the weed is killed or stressed such that its population falls below an economic threshold. This approach works best with introduced weeds. The pathogens used are generally rust fungi, which are capable of self-disseminating through air-borne spores and causing epidemics after initial release. Host density, availability of susceptible host genotypes, favorable environmental conditions, and lack of hyperparasites are important to the success of a classical biological control agent in its new range. Generally, the pathogen is released over small areas and the inoculum is not formulated.

The pathogen used in the microbial herbicide strategy can be native or exotic, although native pathogens have been used more frequently. However, unlike the classical biological control agent, the microbial herbicide agent is mass-cultured and applied as inundative inoculum on the weed (Templeton et al. 1979). If necessary, the inoculum can be applied several times during the growing season to control even the most prolific weed species.

Two examples of success among classical agents are *Puccinia chondrillina*, used to control the skeletonweed *Chondrilla juncea* in Australia (Cullen 1976) and the United States (Emge and Kingslover 1977), and *Phragmidium violaceum*, used against the blackberry *Rubus constrictus* in Chile (Oehrens 1977). In both cases, introduced plants had become weeds and the importation and establishment of the biological control agents controlled the weeds. Other examples can be found in Templeton (1982).

Presently, an isolate of *Phytophthora palmivora* is registered (as DeVine®) and sold in Florida as a microbial herbicide for controlling the milkweed vine *Morrenia odorata* in citrus groves. The pathogen was discovered on dying milkweed vines. Ninety to 100 percent control has been obtained, and the weed is kept under control for at least two years after one single treatment (Ridings et al. 1976, Woodhead 1981).

Colletotrichum gloeosporioides f. sp. *aeschynomene* is registered (as Collego®) for controlling northern jointvetch, *Aeschynomene virginica*, in rice and soybean. The fungus has yielded 93 and 98% control of the weed in rice and soybean over five and six year periods, respectively.

Boyette et al. (1979) have developed methods to use combinations of two fungal pathogens in one application to control two weed species. Smith (1982) is also researching the compatibility of microbial herbicides with chemical pesticides used in crop production systems and the potential for integrating microbial herbicides in pest management systems. Walker and co-workers (Walker 1980, Walker and Connick 1983) have developed a method to produce spores of *Alternaria* spp. used for weed control and for encapsulation of fungal mycelium and spores in sodium alginate globules.

The fungus *Alternaria cassiae*, pathogenic to sicklepod, *Cassia obtusifolia*, has been demonstrated to be a good biological control agent (Walker and Riley 1982) and is being field-tested cooperatively in the states of Arkansas, Florida, Mississippi, North Caro-

lina, and South Carolina. S. E. Lindow et al. at Berkeley, CA, have demonstrated the biological control potential of the smut fungus, *Sphacelotheca holci*, pathogenic to johnsongrass, *Sorghum halepense*, and of *Ascochyta pteridium*, a pathogen of brachen fern, *Pteridium aquilinum* (Webb and Lindow 1981, Massion and Lindow 1983). A native rust fungus, *Puccinia canaliculata*, has been used successfully in Georgia to suppress yellow nutsedge, *Cyperus esculentus* (Phatak et al. 1983). (See following table for examples of current research.)

Research in biological weed control has received impetus and support from a cooperative regional research project, S-136, titled "Biological Control of Weeds with Plant Pathogens." Scientists from state experiment stations, USDA, state agriculture departments, and industry representing 12 states are participating in the project. Suitable biological control candidates are chosen for region-wide research trials. The project has been responsible for most of the remarkable success in this area.

Future developments, it appears, will include commercialization of additional pathogens, combinations of pathogens to control a spectrum of weeds, more effective integration of pathogens with insect biological control agents, chemical pesticides, and better methods of formulation for preemergent and postemergent applications. Although generalizations are not possible, the prospects are bright for using plant pathogens as weed control agents in a variety of crops, forests, rangelands, and waterways. Continued research and cooperation among plant pathologists, weed scientists, industries, and administrators will be essential to maintain the momentum in this field.

Examples of current research on biological control of weeds.

Pathogen-weed	Source
C. gloeosporioides f. sp. *jussiaeae* to control *Jussiaea decurrens*	Templeton 1982 Templeton et al. 1979
C. malvarum to control *Sida spinosa*	Templeton 1982 Templeton et al. 1979
Fusarium lateritum to control *Anoda cristata*, *Sida spinosa*, and *Abutilon theophrasti*	Walker 1981
Cercospora rodmanii to control *Eichhorinia crassipes*	Conway et al. 1978
Araujia mosaic virus to control *M. odorata*	Charudattan et al. 1980
Alternaira helianthi to control *Xanthium strumarium*	P. C. Quimby, Stoneville, MS
Colletotrichum dematium to control *Ipomoea purpurea*	C. G. Van Dyke, A. D. Worsham, and colleagues, Raleigh, NC

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CLOSING REMARKS

A CASE FOR INTERDISCIPLINARY RESEARCH

L. G. Weathers
Associate Dean for Research
University of California, Riverside

Almost two decades ago, in 1966, the National Academy of Sciences sponsored a national symposium in Washington to review scientific advances in pest control. The conference was organized because of growing public protest over the effects on the environment of heavy reliance on pesticides in crop production. The catchwords at that symposium were "Rachel Carson" and "zero tolerance." For some pest control researchers, those catchwords threatened the entire foundation of the great revolution in American agricultural technology that had taken place after World War II.

Biological control was represented at that conference, although one entomologist noted that "its potential had not been fully appreciated." Aside from some contributions in California, Canada, and at the USDA, he said, "relatively little effort has been devoted to its development." These remarks say something about where biological control stood in that period—and they came from a man who was favorably disposed to the discipline.

It was also in that symposium that Donald Chant, then head of the Department of Biological Control at the University of California, Riverside, observed that we needed "a new breed of scientist for research on pest management systems." Unfortunately, he pointed out, the type of research he had in mind would be an unlikely "paragon." He would be a biologist in the broadest sense, but he would also be familiar with genetics, toxicology, population ecology, resource management, systems analysis, biomathematics, and computer programming. Faced with the doubtful prospect that such gifted Admirable Crichtons might ever materialize in the scientific community, Chant issued a call for interdisciplinary research and the team approach to pest management problems. These, he said, were absolutely essential to the future of integrated pest control.

Now, as you know, scientists love to pay lip service to interdisciplinary research. We are always ready to engage in interdisciplinary research—someday! We lift a toast to it at almost every scientific conference, and, having done so, we go back to our separate laboratories to concentrate on our own discipline among familiar colleagues. Don Chant was serious, however, and his views weren't new among biological control specialists. They were shared in the 1960's by his fellow biological control workers at the University of California, Riverside, and by most of the scattered forces of biological control across the United States and abroad.

Biological control was one of the foundations on which integrated pest management was built. Why this shared belief in the necessity for an interdisciplinary approach to pest problems? I think it lay in the fact that the biological control specialist—almost from the beginnings of his discipline in the 1880's—has always been eclectic in outlook. Because his groundings were in ecology, because he appreciated the complexities and fateful interdynamics of ecosystems, because he had learned from hard experience the limitations of biological control, he has always kept a watchful eye on related disciplines. Therefore, he was at the forefront of the integrated pest management movement in the 1960's.

We should ask ourselves if this first national interdisciplinary conference on biological control isn't much belated? Why did it take so long to get together nationally? I think it's partly because there is a lag between new concepts and their incorporation into conventional wisdom. It's taken time for other pest control researchers, agricultural planners, and farmers to fully recognize the limits, burdens, and hazards of unilateral reliance on pesticides after the warning alarms of the 1960's. Perhaps it even required a new generation of pest scientists with a more encompassing understanding of

agroecosystems—those of you who grew up in the 1960's.

However, we can now truly say that biological control and integrated pest management are ideas whose time has come. Almost every agricultural task force or policy-determining group of the past few years, whether on an international, national, or regional level, has placed integrated pest control among the top priorities for agricultural research in the 1980's and beyond. All of these reports agree on the urgent need for more basic research, particularly interdisciplinary, and their emphasis is on rethinking agriculture holistically. In particular, there is an emerging sense that many of the methods of traditional farmers, some of which modern farming had virtually abandoned, need to be reexamined. Such methods are rooted in long practical experience, whether their scientific basis was understood by the farmer or not. Many of these traditional practices—such as crop rotation, crop-free periods, tillage, weeding and harvesting times, and others—can contribute to a balanced crop protection system.

The last three decades of the twentieth century may well be the most critical years in human existence since we abandoned hunting and gathering and took up the plow in neolithic times. Two of the old Four Horsemen of the Apocalypse ride across the twentieth century. As agricultural scientists, we can perhaps do little about the spectre of nuclear war. Disarmament is an issue for nations. But as agricultural scientists, we should be aware that we are all hunger fighters. No agricultural discipline can remain an island, and the battle against the spectre of world famine must be an interdisciplinary fight. The industrial revolution made it possible for us to ignore Malthus for two centuries, but he is now back preaching his message that the resources of the earth are finite and population will eventually exceed the limits of food production.

The population situation is indeed grim, although not perhaps as grim as it was painted by Paul Erhlich, who in his 1968 book, The Population Bomb, declared that the "battle to feed humanity is over." Certainly, the famine that he and other popular writers predicted for the 1970's with hundreds of millions of people starving to death have not come about. That's because food production continued to rise in the 1970's, and some of the developing nations began to deal with their disturbing production problems. In India, for example, there was a 39 percent increase in irrigated land between 1961-1965 and 1978. Between 1975 and 1978, the population of Bangladesh grew by 2.7 percent—remaining among the world's highest—but food production increased by 4 percent.

Nevertheless, world population is still growing at about 2.5 percent each year. There are about four billion people on earth now with an additional two billion more expected by the end of this century. The solution eventually must be a drastically reduced birthrate: perhaps zero population growth. Otherwise, we will be fifteen billion people by the year 2050—living in wall-to-wall megacities. The intermediate solution is improving our agricultural technology, promoting better and more efficient use of our land and water, developing national and international policies that deal with the world's food production instabilities, and helping developing nations strengthen and expand their food production systems.

In particular, as the President's Commission on World Hunger noted in 1980, we will contribute to world food security by protecting our own farming system against deterioration. We need new breakthroughs in increasing crop yield: some of these may come from new basic research in genetics, photosynthesis, and nitrogen fixation. With increasing urbanization of some of our best farmlands, we will need to develop new crops or make it possible to grow crops on land that would have once been considered non-arable. We need to develop new ways to protect our farm systems against environmental damage, particularly loss of soil and water supply. We need to develop field programs of integrated pest management that rely on refined means of pest surveillance and forecasting. With the increasing costs of energy, water, and fertilizers, we have to focus on minimum input agriculture. We are past the time, when we can classify organic farmers as flakes. Their methods are often those of the traditional farmers of the past, and we can learn from them.

Metaphorically, we can learn something from the swill barrel. Some of you may not have heard of the swill barrel, unless you grew up on a farm several generations ago. I grew up on a farm in Utah. Out near the barn and granary, we had a huge wooden

barrel buried in the ground. All of the leftovers went into it--scraps of tomato and apple peelings, all of the leftovers from the dinner table, all of the dishwater, and, finally, an occasional bucket of milk. Throughout the year, the swill barrel bubbled and fermented. It was an endless source of fascination for those of us who were children. Eventually, the swill fermented into a thick slurry, and this slurry was mixed with grain and fed to the hogs.

I'm not suggesting that we restore the old swill barrel. But I think it has a message or us today. It reminds us that many of the traditional farm practices of the past represented sound ecology. On the metaphorical level, however, I think interdisciplinary research is a bit like the swill barrel. It's a means of ensuring that none of our knowledge goes to waste. We need to continue to put our disparate scraps of knowledge together and let them ferment. Out of that ferment, I believe, we will discover some of the new techniques and systems for the agricultural technology of the future.

WORKSHOP REPORTS

SCIENCE OF BIOLOGICAL CONTROL

Section Chairpeople

D. R. MacKenzie
Plant Pathology & Crop Physiology
Louisiana State University

H. C. Chiang
Entomology, Fisheries and Wildlife
University of Minnesota

Workshop Leaders

Taxonomy

L. J. Herr
Plant Pathology
Ohio Agricultural Research and Development Center

R. A. Wharton
Entomology
Texas A&M University

Biotypes

M. A. Hoy
Entomology & Parasitology
University of California Berkeley

S. A. Tolin
Plant Pathology & Physiology
Virginia Polytechnic Institute and State University

Cross Protection

M. D. Summers
Entomology
Texas A&M University

W. L. MacDonald
Plant and Soil Science
West Virginia University

Data Management

D. R. MacKenzie
Plant Pathology & Crop Physiology
Louisiana State University

H. C. Chiang
Entomology, Fisheries and Wildlife
University of Minnesota

THE SCIENCE OF BIOLOGICAL CONTROL

OVERVIEW

An interdisciplinary team of biological control scientists and experts addressed the topic of how to accelerate the science of biologically controlling important agricultural pests. The following four sections are reports of the team findings of Taxonomy, Biotypes, Molecular Processes, and Data Management.

The most commonly identified need of all four groups was communication. As seen from different perspectives, improved communication would avoid duplication, promote assistance between researchers, and promote universality and consistency of research information generated on biological control.

Another item of general concern was a need for improved identification of biological materials (including the host, pests, predators, and pathogens) used in biological control research. Generally, the present methods for identifying biological control materials are too imprecise. New techniques are needed to detect, quantify, and screen biological agents.

The third common area was how best to manipulate biological control as a pest management practice. More research is needed on how the environment affects the successful application of biological controls. Moreover, genetics, in all aspects of biological control, must be better understood. With such information, scientists could improve biological control agents (i.e., induced tolerance to pesticides) and could explain the deterioration or protect the integrity of biological control agent biotypes.

Another area of concern was the safety and the fate of biological control agents in the environment. Much more research is needed on these aspects of biological control tactics. Compliance with existing or future regulations regarding biological control will require a far greater understanding of the relationship of biological control agents to pests, crops, and hosts. Therefore, the safety, fate, and compliance with regulations must be addressed more specifically by the scientists working on biological control.

Finally, biological control successes in agriculture must be documented. This documentation would be used to judge the value and cost of biological control as a pest management strategy.

RECOMMENDATIONS

1. Hold regular meetings of interdisciplinary biological control scientists to report and plan research activities and to standardize methodologies in biological control.
2. Establish a national central repository of information on biological control that would use electronic communication.
3. Recognize the role of service disciplines, such as taxonomy, for their vital contributions to the science of biological control. (Presently, it is difficult for many taxonomists to raise sufficient funds to provide the services necessary for a strong, continued effort in biological activities.)
4. Clarify the systematic status of taxa involved in biological control. The current uncertainties of taxonomy weigh heavily against rapid successes in biological control research.
5. Develop bioassay technologies to quickly detect biotypes and genetic changes in biological control organisms.
6. Fund research in areas such as genetic engineering to determine their potential contributions.
7. Understand the biological relationships in biological control tactics to improve successes.
8. Invest in equipment for biological control research and implementation. The technology of computers, electron microscopes, and others would improve biological control research.
9. Develop ethical standards for biological control research and implementation.
10. Give more research dollars to scientists willing to commit significant efforts to biological control research.

Correct taxonomic identification of the organisms in biological control is essential for (1) developing and applying control procedures, (2) communicating with other scientists, (3) complying with regulatory agencies, (4) evaluating safety, and (5) attaining use registrations. Because the taxonomic needs of entomologists and plant pathologists have uniquely different aspects, they are addressed separately in this report.

ENTOMOLOGICAL NEEDS

The necessity of systematics in biological control programs is reinforced by articles in entomological journals, bulletins, and biological control textbooks. Most federal, state, and university departments with active biocontrol programs also have systematists who actively participate in these programs. The Entomological Society of America (ESA) has a standing committee on systematics resources and a national plan approved unanimously by the voting members in 1974. Despite this support, systematists face severe problems.

Perhaps the biggest problem is the dearth of systematists and funds needed to fulfill the demand for both identification and systematics research. Unfortunately, because of the heavy demand for identifications, research has been sacrificed in favor of the service function. This arrangement may have been workable in the past, but the cost of subjugating research to service has caught up with us.

In the past, the Systematics Entomology Laboratory (SEL) of the USDA provided an identification service that met the needs of most applied entomologists. However, due to recent cutbacks, the SEL has been unable to keep up with increasing user demands. Most of the entomophagous insects used in biological control badly need taxonomic revision. Yet there are insufficient funds to support taxonomic revisions and an insufficient number of employed systematists to do these revisions. Existing literature is full of inaccurate or incomplete identifications; this situation will only worsen under the present conditions.

Applied entomologists requesting identification services have been sympathetic, but have seldom been anxious to work with systematists to solve these problems. However, there are several ways for increasing support for systematics.

To this end, all project proposals in biological control should include, as a line item, budget support for the systematics work needed to complete the project. Administrators must be willing to see that this is actually done for all projects under their control.

To effectively communicate the needs of systematists, the ESA Standing Committee on Systematics Resources should direct their efforts toward lobbying for support in other ESA sections rather than working mostly within Section A.

In addition to the SEL, regional resource centers could be important in identification. Many identifications could be done at a regional level, thus allowing trained systematists to complete the research on which an identifier depends. While systematists have relied heavily on federal identification services, it is time to seek supplemental state, or even international, support. For this, entomologists must speak out, such as writing to their legislators and top federal administrators concerning the vital role of systematics in biological control research.

While cooperation between systematists and users of taxonomic services needs to be improved, systematists also must seek better organization and communication within their discipline. With the present need for systematics research, we can ill afford overlap and duplication. Yet, this is a very real danger because of the current limited communication. Interactive computer systems provide an unparalleled opportunity for solving our research and communication problems.

PLANT PATHOLOGICAL NEEDS

Plant pathology taxonomists have problems similar to those of entomology systematists concerning research and identification. For example, organisms have been inaccurately identified in the literature. These confuse and compound the problems of scientists working in biological control. Revisions of taxonomic classification systems have resulted in non-conformance of many scientific names appearing in older literature as compared with those appearing in recent literature. Thus, research is needed to refine

and clarify taxonomic relationships (basic taxonomic research), and to correctly identify organisms (service research).

Moreover, classical morphology-based taxonomy frequently needs to be supplemented with additional classification (characterization) criteria. For example, plant pathogens can be characterized by pathogenicity as formae specialis on a plant host species level and as races on a variety (cultivar) basis. Likewise, biocontrol agents could be characterized on bases in addition to classical taxonomic criteria. Isoenzyme patterns, serological techniques, whole organism and organelle (ribosome) DNA base ratios, etc., may prove useful in distinguishing effective from non-effective strains and in discovering additional factors important to biological control of plant pathogens.

To implement this, taxonomic research must be expanded. Research is needed in areas such as (1) using new methodologies to help simplify and improve current taxonomic identifications, (2) incorporating new information on species into modern taxonomic treatments of taxonomic groupings currently in controversy and uncertainty, (3) supplementing classical taxonomy with criteria useful for strain or biotype distinctions of value in biocontrol, (4) developing improved methods for inducing the sexual stage of fungi rarely producing this stage, and (5) solving taxonomy and identification problems with computer technology.

BIOTYPES

Biological control depends on good systematics or biosystematics of natural enemies. Alpha taxonomy, which relies principally on morphological characters to distinguish between species, is critically important in biological control, but increasingly, the value of races, strains, or biotypes is becoming recognized.

If two specimens look the same to a taxonomist, they usually are called the same species. If morphologically identical populations can interbreed with each other and produce normal numbers of viable progeny, they are the same species, also. But if the populations have different biological, physiological, or behavioral attributes, then these populations are different biotypes or strains or races.

With parasites and predators, differences in host or prey, host plant, and microhabitat preferences are important in determining the success of biological control projects, and these biological differences may not be associated with morphological differences. These sibling or cryptic are valid species, but cannot be recognized as distinct without detailed biosystematic studies.

All taxonomic categories (strains, biotypes, subspecies, semispecies, and cryptic species) are important in biological control, but detailed studies are necessary to detect them. For example, the parasite *Comperiella bifasciata* has two races or biotypes: the Chinese race prefers California red scale as a host, while the Japanese race, or biotype, prefers the yellow scale. Both biotypes occur in the San Joaquin Valley of California. In the laboratory, they hybridize readily and produce normal progeny and sex ratios, but apparently these biotypes remain distinct in the field.

DISCUSSION

The discussion on biotypes addressed the basic question: "What research is required to enhance/improve the use of biotypes in biological control?" This question was broken down into three subquestions: (a) How can we improve the use of naturally occurring biotypes? (b) How can we genetically improve biotypes through standard breeding techniques? and (c) How can we avoid/prevent deterioration of biotypes?

The workshop was divided into two groups on the basis of potential research techniques: standard breeding methods vs. high technology genetic engineering. Both groups discussed the same questions.

Before discussions began, "biotype" was defined as involving intraspecific variation with respect to biological attributes of parasites, predators, pathogens, antagonists, competitors, and targets. Three assumptions were made explicit: (1) biotypes do exist, (2) biotypes can be important in biological control, and (3) biotypes can be used or manipulated in biological control programs. Ideas generated for each subquestion are found in

Appendix A, 1-4. (Appendix A-5 lists some biological control successes with biotypes.) The following summarizes the major concerns in each area.

STANDARD BREEDING METHODS

Several high priority research areas surfaced during the discussion of subquestion (a). In order of importance, they were (1) identifying the traits important in naturally occurring biotypes, (2) developing methods for detecting, identifying, and quantifying biological and ecological differences among biotypes, (3) selecting biotypes from disease suppressive soils—a promising area of research, (4) understanding when and where biotypes develop under natural conditions, and (5) selecting biotypes that colonize the rhizosphere.

High priority areas in subquestion (b) were (1) develop new biotypes with enhanced biological control abilities, and (2) develop sensitive bioassay protocols for selective microbial pathogens. Attributes other than pesticide resistance should be subject to genetic improvement, but it is necessary to identify useful/important traits to be selected or improved. Rarely are factors or traits identified that limit the effectiveness of biological control agents.

The next high priority area was producing or identifying visible genetic markers. This suggested that genetic manipulations in the laboratory and field can best be done if additional genetic tools are available. Basic genetic information is rarely available for economically important biological control agents. Research also is needed to develop heterosis in biotypes of imported natural enemies of pest arthropods. This method could improve establishment rates in natural enemy releases. The heterosis might allow selection of the most adapted strains after release. Improved and effective mass-culture techniques are necessary to allow genetic selection of biotypes. The ability to rear biological control agents effectively for either inundative or inoculative releases is often a limiting factor.

Overall, genetic selection of biological control agents promises to solve certain problems, but much more research remains to be done. Lack of knowledge of the fundamental genetic bases of desirable traits, such as host selection and temperature tolerance limit, current research. Maintaining genotypic and phenotypic quality during colonization and the ultimate competitiveness of artificially-selected biotypes will be important to improving biotypes, also.

For the last subquestion, two priority areas were identified. Developing rapid bioassay mehtods to detect biotype deterioration is highly desirable, as is standardizing quality control monitoring techniques. Once improved strains have been developed, genetic and cultural methods must be available to maintain them. Discussion about research needs in this area focused on documenting successes in genetic improvement projects. Up to now, the main hindrance to research (and funding) has been the lack of success in the field with genetically improved biological control agents. The recent successes with laboratory-selected, pesticide-resistant strains of predatory phytoseiid mites (*Metaseiulus occidentalis* and *Amblyseius fallacis*) could generate additional interest, as could laboratory selection of *Trichoderma viride* for resistance to benomyl.

GENETIC ENGINEERING

This group addressed the same subquestions as above, only from a "high tech" (molecular) approach. Research needs in this area were as follows (see Appendix A-4 for the list of ideas generated). Presently, there are no examples of genetically engineered biological control agents. However, microorganisms, such as viruses, fungi, and bacteria, are prime candidates for genetic engineering. Success with these organisms is likely to occur sooner than with eukaryotic biological control agents.

1. Determine the stability of engineered biotypes in the environment. This would include recombinant organisms, mechanisms of instability, the evolution of biotypes in an agricultural environment, and the genetic response of the host to bioengineered organisms.
2. Identify biotypes through specific genetic and serological markers; develop *in vivo* methods and gene probes.
3. Develop culture collections and/or an information network of engineered agents indexed by desirable traits.
4. Understand how engineered organisms affect the environment by developing protocols for safety testing and registration, examining induced changes in organisms in the ecosystem, learning if

introduced genes are transferred to other organisms, and studying the ramifications of survival windows of the engineered organism.

GENERAL CONCLUSIONS

1. Attributes of biotypes that contribute to successful biological control are not clearly defined; therefore, research must be directed at identifying such attributes.
2. Once desirable attributes of biotypes have been identified, methods for screening for them are necessary. Efficient detection methods should be developed.
3. Genotypic and phenotypic changes occur during the rearing of biological control agents. Genetic and other methods of identifying deteriorated biotypes should be developed, as solutions to rearing problems probably have a genetic component.
4. Genetically improving biological control agents using standard breeding techniques and high technology methods will solve certain problems in biological control. Research should be supported to select for pesticide resistance in natural enemies important in entomology, plant pathology, and weed science. Research to improve other attributes should be supported also, although the genetic basis of other traits may be polygenic, which makes these attributes more difficult to work with. Research on the long term persistance of the improved agents in the environment should be supported, also.

MOLECULAR PROCESSES

Many naturally occurring microbial agents pathogenic for insect pests and noxious plant species have been identified as potentially useful biological pesticides. Interest in the commercial development and use of microbial agents in integrated pest management strategies has developed because microbial agents differ from chemicals. They do not exhibit the broad host range of chemicals; therefore, they are safe for natural predators and beneficial insects. Their effective use in IPM programs will reduce dependency on chemical pesticides. They have no known pathogenic or toxic effects to humans and other non-target organisms, and insect resistance to microbial agents is less common or develops more slowly than for chemical pesticides.

Expanded commercial development and use of microbial insecticides depends on discovering useful agents and developing genetic engineering technology to improve virulence and environmental persistence or broaden host range within acceptable limits. However, effective application of these methodologies for genetic manipulation is limited by an insufficient knowledge of those factors controlling host specificity and virulence and the mechanisms by which these factors are expressed and regulated in the insect host.

Furthermore, several plant and animal viruses are transmitted by insect vectors. These viruses have evolved with both kinds of eucaryotic hosts exhibiting significantly different pathology for the insect vector and plant or animal host. Although in general they may have similar mechanisms for gene regulation, the regulation and expression of certain virus genes, which are host dependent, are significantly different. Defining those mechanisms at the molecular level will facilitate beneficial genetic manipulation of pathogenicity and will provide new approaches for controlling disease transmission. To accomplish this we need to understand the elements that control gene expression in plants and insects and how pathogenic agents can exploit those elements.

In contrast to entomology, using microbial agents (i.e. viruses and mycoplasmas) to biologically control plant pathogens is rarely done. This partly stems from our inability to recognize potentially useful systems that already exist. For the known systems, there are inherent problems in transmitting microbial agents within the population of a specific organism. Attenuated virus strains or saprophytic microbes that induce resistance to damaging pathogens are closer to being used. Numerous potentially useful systems have been documented, but understanding and exploiting the mechanisms associated with in-

duced resistance are still being researched.

To assess research for discovering and improving microbial agents useful in biological control, the workshop addressed two questions: "How can we better identify systems at the subcellular level that could be exploited for biological control?" and "What are the most feasible experimental approaches to the study or use of available systems to control plant diseases on insect pests?" The following items were listed by the discussants as having high priority.

IDENTIFICATION OF SUBCELLULAR SYSTEMS

Molecular Mechanisms of Host Specificity

The fundamental concern was that without understanding the molecular basis for host specificity there would be little appreciation, or ability, to search for or recognize mechanisms related to induced resistance or to identify the mode of action of microbial agents. The genetics of these pathogen-host relationships are complex and are continually evolving. Keeping informed of the research on pathogenic mechanisms at the molecular and cellular level of the better studied animal and plant pathogens should improve our understanding of these relationships.

Improved Identification and Detection Techniques

The molecular agents that have been identified were discovered because they produce readily observable beneficial effects. Undoubtedly, more subtle, but equally important, biocontrol systems or strategies exist that can be investigated at the molecular level. Therefore, systematic surveys must be conducted of insect and plant pathogen populations of interest. Surveys could include known microbial agents, agents in target or closely-related species, and foreign sources for promising agents. Techniques to enhance host symptom expression are needed, also. These should emphasize highly sensitive detection with specific molecular (nucleic acid and serological) probes developed from recombinant DNA and monoclonal antibody techniques.

Gene Products Associated With Resistance

Historically, one of the most effective means of combatting plant diseases and pests is with resistant plant varieties. In contrast, virtually nothing is known about how insects confer resistance to microbial infection or the transmission of pathogenic agents. For insect control, host factors (specific host proteins and host immunity mechanisms) conferring resistance could be bypassed by genetically altering the pathogen. Plants inoculated with pathogens frequently exhibit enhanced and broad-spectrum resistance to subsequent infection. This has been observed with bacterial, fungal, viral, and nematode infections. Similar responses can be elicited by applying either attenuated pathogenic strains or fractions of pathogens to some hosts. Although the mechanisms are not understood, the potential to manipulate these systems relative to plant disease symptoms and disease transmission through standard procedures or genetic engineering technology will strongly impact agricultural productivity by (1) altering the host for resistance or (2) altering the pathogen for non-transmissibility or for non-pathogenicity in the plant or animal.

Information and Reporting Bank for Microbial Agents

Assembling detailed information about molecular agents, their activity, and potential usefulness would help coordinate research efforts. In addition, future consideration could be given to maintaining a repository of useful agents.

EXPERIMENTAL APPROACHES

Mechanisms of Infection and Pathogenicity

We need to identify the agents, host factors, and physical conditions resulting in infection. By controlling these, we can control infectivity or disease processes. For insect control, one goal should be to identify genetic factors of the host or microbial agent that could be altered to optimize or enhance infection. For plant disease control, genetic factors or physical conditions, which might be altered to attenuate the disease process, could be manipulated.

Genetic Manipulation

Standard genetic techniques and genetic engineering technology are the main research approaches that should be used to enhance agent performance, to identify and clone genes related to host specificity and virulence, and to develop molecular cloning vectors for altering, introducing, or expressing desired gene products in organisms. Genetic engineering will help elucidate the very complex and poorly understood molecular

genetics of pathogenesis in eucaryotic organisms and will play a major role in (1) increasing our understanding of the mechanisms of pathogenicity, (2) permitting early detection of infection for plant pathogens or enhancement of insect pathogenic agents, (3) providing more direct control of disease symptoms and pests, and (4) engineering the pathogen for some beneficial application.

For plant pathogens, genetic factors and gene products that will induce resistance to plant pathogens and insect pests or discourage predators should be studied. Pathogenic agents for insects could be genetically altered to enhance infectivity and virulence. The complex functions of most of these systems, which involves many genes of unknown identify, makes them difficult to exploit.

Progress has been slow in plant systems because the knowledge of the molecular biology of plant systems lags behind that of animals and certain viruses and microorganisms. Also, the lack of comparable molecular vector systems and transformation markers has inhibited the broader application of genetic engineering experiments in plants.

Genetic engineering techniques for manipulating DNA sequences and molecular vectors do exist for the introduction of foreign genetic material into animal viruses, bacteria, and their hosts. Because of this, the genetic engineering of microbial insect pathogens to develop more potent or virulent strains has very good potential and promise.

Host Tolerance and Defense Mechanisms

Host tolerance and defense mechanisms to plant pathogens and diseases should be studied to identify new ways to use insect pathogens and to control plant diseases. Once the genetic mechanisms for these traits have been identified in plants, the mechanisms for tolerance or resistance can be manipulated to combat disease. For insect pests, identifying the factors that allow plant viruses to be transmitted by insect vectors might enable scientists to then interfere with those processes. For microbial pesticides, control could be enhanced by specific knowledge of host resistance mechanisms that could be bypassed by genetic manipulation.

***In vitro* Systems**

Plant and animal cell and tissue cultures provide standard systems and conditions for controlled experiments on infection and disease processes in plants and insects. These systems allow subcellular-level experiments that cannot be carried out in the organism. Mechanisms in disease processes, pathogen-host interactions, and the genetic control of these processes would not be as clearly defined if comparable studies were conducted in organisms. Indeed, studies using *in vitro* and organismal systems are needed, but *in vitro* research on microbial agent-host interactions has been the major approach for investigating gene structure and function in the eucaryotic system—both of which must be understood for effective biological control of diseases in plants or use of microbial agents for pest control.

Virulence and Molecular Agents

Once potentially useful agents that decrease virulence and survival of plant pathogens or increase virulence of insect pathogens are identified, methods of enhancing their replication and spread in the population can be sought. Some agents may have broader applications if they can be transmitted to other organisms and cause corresponding detrimental effects. It has been more difficult to identify useful molecular agents and to develop methods to introduce and transmit them to biologically control plant pathogens than it has been to biologically control insect pests.

Additional Research

Other research approaches considered were biological vectors of protecting agents, mass propagation techniques for microbial agents, additives to increase infectivity and persistence, evaluating the benefits of multiple agents or mixed infections, and environmental fate and safety of microbial agents.

DATA MANAGEMENT

Scientists representing entomology, plant pathology, regulatory agencies, and the USDA-ARS addressed the topic of data management in relation to biological control. The group focused on the question: "What are the barriers to better biological control data

collection, management, and exchange?" After a period of idea generation and recording, the items (see Appendix B) were discussed. Three priority needs were identified: universally acceptable systems to better manage biological control data; effective communication between scientists and agencies; and knowledge of what data bases, information files, and literature are available. These priority items were then separately grouped into categories.

ORGANIZATION AND OPERATING SYSTEMS

Universally acceptable systems to better manage biological data must be developed. Scientists need uniform format, equipment, and procedures to manage the data related to biological control. Systems, not just one, are needed to accomplish the multiple tasks of data management.

Other items that were seen as barriers were (1) inconsistency in reporting results and taking ratings, (2) inadequate sampling methods, (3) lack of an overall organization for data management, (4) an inability to precisely identify many biological control agents, (5) the incompatibility and/or absence of interchangeability of computer programs for data management (software) and equipment (hardware), (6) lack of cross-referencing of information, (7) difficulties in recording relevant environmental parameters, (8) too few trained personnel (technicians) willing to participate in a unified biocontrol data management system, (9) general unacceptance of the need for a central repository of information on biological control, and (10) absence of knowledge on the source of biological control agents and their use.

INFORMATION NETWORKING

Developing effective communication networks using communication technology would increase the exchange of information and probably increase the application of new technologies. All biological control workers, including federal and state governments, universities, and other institutions, would be part of this network. Also, knowing what data bases, information files, and literature are available would benefit biological control researchers, administrators, and regulatory agencies. Scientists need to become familiar with computers for data management tasks and how to use computers to obtain biocontrol agent data.

Inadequate funding in some applications now limit the extension of the existing USDA-ARS biological control data management system (presently well funded) to other potential users—this deserves attention. Moreover, the unavailability of equipment to receive, transmit, store, or process biological control data severely limits the establishment of a national or international network of biological control data management systems. Similarly, interpretative models need to be developed to assist scientists in looking for success patterns of biological control. Such models will increase our understanding of how best to use biological control.

PROFESSIONAL ATTITUDES, ETHICS AND STANDARDS OF CONDUCT

Participants gave examples of scientists hesitating to release information on biological control agents for fear of being "scooped" in publication or on patents and/or royalities. Other difficulties were perceived to originate from a lack of communication between scientific disciplines, competition between individuals, and even competition between disciplines and institutions. Government regulations were also a source of frustration in access to and in dissemination of biological control data.

Discussion then focused on the existing USDA/ARS biological control data management system. Jack R. Coulson described the recently established ARS biological control documentation center. Suggestions were made to extend this system into a national network with the potential for international linkage. Two mechanisms could be used to implement this objective: (1) a CSRS/SAES cooperative agreement on biological control data management, and (2) a regional technical committee. As a CSRS Cooperative Agreement with Minnesota Agricultural Experiment Station on the survey of biological control agents, and an NCR-125 technical committee on biological control of arthropod pests already exist, a national biological control documentation center could be organized with minimal effort—a highly recommended goal.

EVALUATION AND ANALYSIS

Section Chairpeople

R. Baker
Botany & Plant Pathology
Colorado State University

D. L. Haynes
Entomology
Michigan State University

Workshop Leaders

Sampling

L. Johnson
Entomology & Plant Pathology
University of Tennessee

R. L. Jones
Entomology, Fisheries and Wildlife
University of Minnesota

Population Dynamics

G. E. Templeton
Plant Pathology
University of Arkansas

S. M. Welch
Entomology
Kansas State University

Integrated Pest Management

D. L. Haynes
Entomology
Michigan State University

R. Mankau
Nematology
University of California
Riverside

Economic Thresholds

S. V. Beer
Plant Pathology
Cornell University

F. L. Poston
Entomology
Kansas State University

EVALUATION AND ANALYSIS

OVERVIEW

Predictably, the concerns emphasized in this section of the conference, which dealt with the evaluation and analysis of biological control, were quantitative. Discussion in three of the sections—economic thresholds, integrated pest management, and population dynamics—all stressed the need for adequate sampling techniques, the subject of the fourth workshop.

Reliable techniques for measuring distribution are needed not only for biological control agents, but for the target organism or pathogen. Sampling techniques must provide information for decisions on economic thresholds. Without such data, reliable thresholds for implementing biological controls cannot be practically applied. The theoretical basis undergirding such interactions must be understood before the systems can be modeled.

Currently, sampling techniques cannot adequately determine population density, activity, or survival of biological control agents. Similarly, we must know how the agent impacts the pest population, as measured by these same parameters. With multipurpose sampling techniques, the activity of biological control agents in integrated pest management programs can be monitored.

Primarily the host and environmental factors influencing the activity of biological control agents must be identified. Perhaps this is the least understood subject, especially in ecosystem-simulated analysis and soil ecology. Integrating such broad areas of research with multiple pest problems will require interdisciplinary research and communication over long time intervals.

By its nature, the nominal group technique directed discussion toward highly specific questions. While providing maximum participation, it did so at the expense of an integrating framework that effectively defined the subject area. The workshops in this section deal with an identical universe—a crop, a pest, a biological control agent, and the abiotic and biotic environment—from different perspectives. Thus, by focusing on sampling, we avoided concerns for <u>why</u> we are sampling: IPM avoided non-crop involvement, population analysis avoided community evaluation, and economic threshold avoided long-term ecosystem evolution. Clearly, a single system can be viewed from an infinite number of perspectives, but we should realize that what is excluded by this approach is undoubtedly more important than what is in our narrow concerns.

Understanding an ecosystem as it exists in the real world through time and space must be a fundamental goal of all participants in biological control. Our tools will be quantitative, and the complex of interactive life systems will require computer-aided analysis. For biological control to work in complex ecosystems, which now rely on heavy applications of pesticides, we must manage the entire ecosystem. This is not a simple problem, and the underlying science that can support the effort must be expanded and recognized for its essential contribution. Understanding biological control systems, both successful and non-successful, is an excellent entry point into the subject of ecosystem analysis.

RECOMMENDATIONS

1. Conduct regional long term studies on the population dynamics of interacting populations of biological control agents, with the goal of tracking populations through several life cycles. Such studies will increase our understanding of the basic principals of biological control.
2. Study the life systems of biorationals and explore the mortality-inducing phenomena for the agent and the host.
3. Coordinate and disseminate information on biological control agents. This includes organizing biological control activity such that individual scientists can participate in national programs.
4. Fund and develop rapid identification techniques for biological control agents.
5. Expand research in ecosystem simulation analysis. This area has the potential to enhance biological control through management practices.

Progress in the effective use of biological control agents depends on a better understanding of the parameters affecting the agent/pest populations. Such parameters include the insect's (a) behavior and distribution, (b) interactions with other trophic levels (i.e., ratios and density relationships), and (c) response to abiotic factors. Crucial to this understanding is an ability to describe and predict changes and impacts of these parameters, preferably via a mathematical model. The development of this model and the model's usefulness is limited by the quality of the input—input provided by sampling.

Sampling requires decisions about detection methods, type of data, levels of accuracy, and insect distribution. Improved sampling can result from improvement in any of these components. Ideally, sampling should provide the most accurate estimates of populations at the minimum costs. Given unlimited time and resources, sampling technology is adequate to produce acceptable estimates. Unfortunately, resources are continually becoming more limited. The chore of this workshop was to identify routes or barriers to more efficient sampling.

The participants in this workshop were divided into two subgroups to address different questions. Group A addressed the question "What are the weak links in sampling technology relative to biological control agents?" Group B addressed the question "What new sampling research ideas would produce the maximum return in increasing the effective use of a biological control agent?" After the groups generated a list of answers (see Appendix C), the ideas were prioritized. The following is a discussion of the most important ideas.

IDENTIFICATION AND ISOLATION

Both subgroups were concerned about the lack of techniques, particularly rapid techniques, for identifying biotypes, strains, and races of biological control agents. Growers need these methods as well as researchers. New selective media for isolating new biological control agents was of particular concern to plant pathologists. These new media are critically needed for isolating soil-borne microorganisms and to assess their biological control potential.

DETECTION

The need for sensitive, practical detection methods, particularly for low density and clumped organisms, was expressed by both groups. This includes developing sensitive, practical, detection and sampling methods that are effective over time and space. More specifically, semio-chemicals would be an important tool for detecting low-density insect and microorganism biological control agents.

DISTRIBUTION

The primary problems of recognizing and sampling from variable distributions were seen as (1) determining patterns of horizontal and vertical dispersion and distribution, (2) estimating age-specific natural enemy mortality, which expresses the impact of variable distribution patterns of various ages of organisms, and (3) developing better techniques for measuring distribution at subsites, which was a particular concern of plant pathologists.

MULTIPLE SAMPLING TECHNIQUES

Sampling more than one species and/or using the same sampling methodology for multiple purposes can be very difficult. For example, it is difficult to determine predator, prey, and plant phenology in synchronous relationships and to estimate age-specific natural enemy mortality, as sampling of various ages can be analogous to multiple species sampling.

Sampling techniques that would accumulate data for multiple uses are needed. These techniques would be used in interdisciplinary efforts. Also, techniques are needed to measure agent-pest ratios as well as the agent's impact on other associated organisms. Knowing when a biological control agent is operating and what factors enhance biological control is highly important to researchers. Studies also should be conducted to develop techniques for sampling biological control agents in multi-pest and multi-habitat situations as well as sampling multiple agent-single pest systems.

SAMPLING METHODS

Both groups expressed the need for im-

proved sampling methods. Fast and reliable counting methods and simplistic sampling techniques for growers are highly important for IPM implementation programs. Such techniques would include identification and quantification methods. The potential impact of environmental changes and/or cultural practices (i.e., reduced tillage) on sampling technology was recognized. Participants expressed concern that reduced tillage and no-tillage could dramatically shift population densities and distributions in field crops.

SUMMARY

The large number of ideas generated partly reflects the diversity of the participants. The slant of the workshop was to explore sampling ideas that represent potential interdisciplinary efforts. From that standpoint the workshop was successful. Such items as identification of organisms, detection at low densities, recognition of and quantification of biological control agents, and sampling from variable distributions, all have strong interdisciplinary support.

POPULATION DYNAMICS/MODELING

Biological control, by definition, involves an interaction between the target organism and one or more biological control agents—an interaction that is dynamic in both time and space. Understanding and being able to predict or model these dynamics is important to pest management decision-making, discovering or evaluating biological control agents, and modifying or exploiting biocontrol mechanisms to practical advantage.

These reasons and others led this workshop to consider the question: "What research is needed in population dynamics and/or modeling to advance the science of biocontrol?" The group was divided into two panels, and ideas were developed and discussed separately (see Appendix D). A discussion of the items rated highest priority by the two panels follows.

To study the dynamics of populations, researchers must be able to measure population levels of individuals of the biotic systems. Therefore, research must go into improving techniques for detection, identification, and quantification of organisms with potential for biological control and their target organisms. This need is particularly acute with microscopic plant pathogens where even the presence or absence of a target or agent organism is hard to determine.

Factors critical to the population dynamics of target or agent organisms must be identified. This requires research into the life cycles of individual species, both in the field and under controlled conditions to understand constraints or stimulants to epidemic or epizootic buildup. More specifically, research is needed to understand intrinsic control of populations at the organismal level.

Incorporating environmental influences in population dynamics also needs to be addressed. Specific research must address the microhabitat influences operating at the exact site occupied by the organisms to understand extrinsic control factors. More general research would deal with characterizing the geographic and seasonal environmental factors that influence populations.

GROUP A

Beyond this, several issues were unique to each group. Group A identified three major areas. Of critical importance in understanding population processes and/or managing them is understanding temporal sequencing and schedules. Therefore, research is needed to develop models of the phenological relationships between hosts, pests, and biological control agents. Studying the population dynamics of the target or agent organism at low or endemic levels is particularly important. Such studies, although difficult, might reveal reasons or useful mechanisms that could be exploited to advantage. Additional research is needed to understand the relationship between host population structure and consistence or persistence of biological control agents. Age class structure can have dramatic effects on biological control success due to the varying susceptibilities of different target organism life stages to attack. Understanding these relations better would increase biological control effectiveness.

GROUP B

Group B identified four priority research areas in addition to the above topics. (1) Most important was understanding the population genetics aspects of biological control. This involves a variety of features including inherent genetic differences between different individuals in a species and selection pressures that may operate during or resulting from biological control programs. (2) Research must be conducted on the behavioral interactions between agent and host organism. Often the nature of an interaction may be modified by behavioral traits, such as predator avoidance, searching and movement. Another aspect includes behavioral responses to environmental factors that may influence reproductive, developmental, or other processes important to population dynamics. (3) More long term studies must be conducted on population changes. Certain aspects of population dynamics important to biological control are only visible over multiple season periods, such as species succession and long term population oscillations. (4) Understanding the mechanisms of biological control (i.e., antagonism, antibiosis, pathogenesis, substrate colonization) was of particular importance to plant pathologists. Understanding these mechanisms more thoroughly improves the potential for artificial enhancements or manufacture for practical use of biological control agents.

INTEGRATED PEST MANAGEMENT

Integrated pest management is not clearly definable from other, more classical, plant protection approaches. In this respect, "biological control" shows similar definition problems in large heterogeneous groups of scientists. Basically, this workshop was to determine the high priority researchable questions associated with the loosely defined, abstract concepts of biological control as they interact with the highly fragmented, abstract concepts of IPM.

The workshop was divided into three groups, each addressing slightly different questions. (1) What information is needed to effectively use biological control in IPM systems? (2) What are the research needs in IPM that will advance biological control programs? (3) What are the research needs in biological control that will be most important to IPM programs? (See Appendix E for compiled list of research needs.)

While the workshop was underway, each of the three groups attempted to identify five high priority researchable questions. The major issues (unranked) were as follows.

1. Analyze the interaction of organisms in crop production systems.
2. Evaluate the impact of biological control agents in ongoing IPM programs.
3. Develop detection and sampling methods for biological control agents and pests at low densities.
4. Develop accurate and rapid methods to identify species important to IPM.
5. Develop predictive capabilities for biological control interactions.
6. Develop management information concerning root growth and predisposition of host plant.
7. Identify and study gaps to understand the basic biology of biological control agents in pests.
8. Model predator-prey relationships.
9. Survey biological control agents in IPM programs.
10. Analyze the compatibility of biological control agents with other control methods (e.g. chemicals).

Although these issues represent the views of participants, they do not delineate the subject area in a coherent fashion. Using the ideas generated by the three groups (Appendix E), the following six areas were defined as representing the breadth of the workshop.

BIOLOGICAL CONTROL INFORMATION

Research is greatly needed in basic taxonomic studies, especially the rapid identification of individual parasites and pests collected from an ecosystem. Access and availability of information relating to biological control activity is also a critical area. Educational programs for both the classroom and the general public need to be developed, and more information is needed concerning handling and rearing of pests and parasites. Information on biological control agents must

be coordinated and disseminated. CR/USDA should provide summaries of research activity or new biological control programs and should systematically organize biological control activity so individual scientists can participate in national programs.

MANAGEMENT TECHNIQUES TO ASSIST BIOLOGICAL CONTROL IN IPM

Five areas were identified as particularly important:

1. Modify plant breeding programs to take full advantage of biological control methods, such as developing canopy structure, studying root morphology and exudates, and insuring alternative food resources and predators.
2. Improve biological control agents.
3. Research spray technology to target pesticides to differentially kill pests and parasites.
4. Emphasize cultural control practices, including cover crop, rotation, and interplanting.
5. Design farm equipment to increase the effectiveness of biological control agents.

ECOLOGICAL METHODS

The primary factor limiting our reliance on biological control is basic research on the fundamental aspects of monitoring ecosystems. Sample methodology for the abiotic and biotic components of an IPM production system is greatly needed. This is tied into modeling components of the pest-crop ecosystem. Both sampling and modeling are critical to developing economic thresholds, which are critically needed for biological control agents as well as pesticide management.

ECOSYSTEM ANALYSIS

Increasing our understanding of the pest-crop ecosystem has several levels of prob-basic life cycle information is lacking, and research on the population dynamics of hosts and parasites needs to be greatly expanded, particularly in biorational life support systems—other than those associated with the primary host or prey.

Little progress has been made in ecosystem simulated analysis—which has the potential of assisting managerial practices to enhance biological control. For example, little is known about soil ecology, yet it is perhaps even more important than the above-ground components.

Research on pest dispersal to and from non-crops and between crops is needed, particularly where pests and parasites move to attain their life support.

ECOSYSTEM MANAGEMENT

In pest-crop systems that rely on heavy pesticide applications, research is needed to evaluate the transition from such a high state of dependency to a lower level of dependency. This problem is particularly difficult with multiple crop pests. Unfortunately, this type of research is expensive and usually only motivated by crises. However, research methodology to do this must be developed, including detailed economics analysis. Interdisciplinary research and funding over long time intervals is required to conduct such research.

INSTITUTIONAL CONSTRAINTS AND EVALUATION

Regulations and their impact on control options must be evaluated. Regulations often influence how biological control practices will perform; they effect economic thresholds, environmental quality, and public attitudes concerning quality. Research should consider regulation as an integral part of IPM programs. Much more research on economic evaluation of various management approaches must be undertaken, particularly with rapidly increasing production costs.
lems. One of the most critical areas is simply understanding the basic biology of a species within its production system. Also,

ECONOMIC THRESHOLDS

For the past 20 years, the economic injury level concept has been generally accepted as the backbone of progressive management programs. The concept serves as the economic foundation in decision-making processes. The economic injury level has been defined as the lowest population density causing sufficient injury to justify the cost of

artificial control measures. In this workshop, an implementation-oriented concept was proposed: the economic threshold. This term has been redefined as the decision level chosen such that there is little likelihood that the real management system might inadvertently permit the pest population to exceed the economic injury level.

These definitions show that the concept of economic injury is intended for programs requiring management decisions. In conventional programs, the management decision usually involves the application of some curative control measure, such as a pesticide. In this context, the threshold concept applies to (1) biological control programs that involve augmentative or inundative releases of natural enemies and (2) management programs that incorporate natural control in management decisions. One may question, however, the utility of the concept to traditional introduction programs in biological control. The concept is not conventionally used to make management decisions to apply preventative controls. This important issue was not addressed in the workshop.

After consultation with plant pathologists and entomologists, the question "What research is needed to further the use of threshold-based management programs that incorporate biological controls?" was selected for discussion. The workshop was separated into two groups because of the number of scientists in attendance. (See Appendix for consolidated list of research needs.)

GROUP A

The group was asked to define the term "threshold." Although there was no generally accepted concept, most members agreed that "threshold" involves the attainment of a certain pest population or inoculum level that dictates the implementation of management actions directed towards altering subsequent damage to plants from the activity of the pest.

With this definition in mind, the group prioritized their research ideas. The major priority items were as follows.

1. Develop simple predictive tools for making field decisions, including not only the appropriate theoretical models (including thresholds) but also sampling and assessment techniques.
2. Determine the theoretical basis for thresholds, including the validity of thresholds.
3. Determine thresholds within the context of the ecosystem. Such research would determine thresholds for an agroecosystem, rather than considering only the crop. It also would involve beneficial or detrimental uses of a biological control technique, rather than just the potential of the technique to affect the target pest.
4. Develop improved techniques for establishing thresholds.
5. Determine the influence of environmental and host-plant factors on thresholds. Host-plant and environment may influence thresholds—sometimes in a complex manner.

Research is also needed to forecast pest activity, develop thresholds specifically for biological controls (as opposed to those appropriate to chemical controls), and design epidemiological (plant disease) models.

GROUP B

After discussion of the ideas, the group prioritized their top seven research suggestions. The following are those major research areas.

1. Establish economic thresholds for target species or complexes of target species. The phrase "target species or organism" was adopted to eliminate confusion between terms such as pest species or disease organism. The key component lacking in most threshold-based management programs is adequate economic thresholds. Other research suggestions, which did not rank as high, dealt with implementation problems concerning thresholds of multiple target species.
2. Forecast short- and long-term changes in target population density in annual or perennial crops. "Crop" applies to all produced items, such as forests, apples, or cotton. The length of the forecast depends on the number of generations of interest in the target species. This period may be short, as applied to some diseases or multivoltine insect species, or long, as applied to some weed and univoltine insect species.
3. Quantify the impact of biotic agents on target organisms, including the positive and negative impacts of complexes of biological control agents on target spe-

cies.

4. Sampling and monitoring procedures to forecast use of biological control agents.
5. Survey, identify, and categorize heretofore unknown indigenous control agents. This is an especially perplexing problem. At present, one of the best methods of identification is by accident.
6. Develop rapid methods for sampling biological control agents for use in threshold-based management programs. Research should emphasize implementation.
7. Delineate and quantify the effects of abiotic factors on biological control agents in cropping systems. Although the effects of some of these factors on target species have been quantified, they have not been addressed with biological control agents.

CONCLUSIONS

Developing reliable thresholds is critical to properly manage production systems. Although this research area has received some attention in the last decade, it is disproportionately low compared to population dynamics and the development of new control strategies. This situation may be a product of overspecialization in scientific disciplines. Each specialist views his or her discipline in detail; other disciplines are "black boxes" containing simple inputs and outputs. Developing a practical implementation tool, viz a threshold, requires a relatively intricate understanding of the biological relationships between the pest-disease complex, the crop, the environment, potential management strategies, and the economics of the system. Introducing biological control agents into this system increases its complexity.

The prioritized list of research needs reflects the complexity of these systems. Participants in the groups identified research needs required to (1) achieve a better understanding of the intricacies of these systems and (2) attain implementation status for biological control agents in threshold-based management programs.

Although a number of the priority items in this workshop reiterate those mentioned in previous sessions (Sampling, Population Dynamics, and IPM), they should not be dismissed as overkill. Rather, they represent key research needs that must be met before certain types of biological control programs can be fully implemented into production systems.

Section Chairpeople

R. Charudattan
Plant Pathology
University of Florida

K. S. Hagen
Biological Control
University of California
Berkeley

Workshop Leaders

Technology of Introductions

T. Kommendahl
Plant Pathology
University of Minnesota

G. Gordh
Biological Control
University of California
Riverside

Quarantine Technology

W. H. Ridings
Plant Pathology & Physiology
Clemson University

T. W. Fisher
Biological Control
University of California
Riverside

Foreign Exploration

R. Charudattan
Plant Pathology
University of Florida

D. Gonzalez
Biological Control
University of California
Riverside

Increased Effectiveness

H. C. Hoch
Plant Pathology
New York State Agricultural
Experiment Station

K. S. Hagen
Biological Control
University of California
Berkeley

PRACTICE AND IMPLEMENTATION OF BIOLOGICAL CONTROL

OVERVIEW

Much work needs to be done in the four topics discussed in this section. Biological control agents should be introduced into target systems such that success is assured. For biological control agents of foreign origin, quarantine technology is important. Quarantine aspects should be decided and procedures should be established before initiating foreign exploration to enable orderly research and implementation. Aspects of foreign exploration need critical attention on the part of agencies, administrators, governments, and researchers, because social, economic, and political considerations usually affect this area. Increasing the abundance and effectiveness of biological control agents, both exotic and native, also should be continually emphasized to assure long-term success.

Important research aspects under the technology of introduction include the timing of application of the biological control agents, production of inoculum of microbial and macrobial biological control agents, formulation technologies, delivery of the biological control agents into favorable environments, and genetic improvement of biological control agents.

Effective quarantine technology depends on adequate facilities, proper training of personnel in handling biological control material, reliable taxonomic procedures for identification, and information retrieval systems. Most importantly, regulatory bottlenecks should be avoided.

To be successful in foreign exploration, there must be a clear understanding of the basic ecology of the biological control agent and the target pest. Good cooperation and coordination of efforts is necessary between researchers, agencies, and governments. The biotypes of the pest and the biological control agents should be clearly understood; surveys should be conducted in the most appropriate foreign sites to yield fruitful results; and biological control information should be easily accessible through a data bank. Most significantly, administrative support is needed for foreign explorations.

Once initiated, a program must be continually monitored to assure the abundance and effectiveness of native and exotic biological control agents. This may be accomplished through chemical, nutritional, or physical manipulations of the environment to favor the biological control agents or to alter their behavior or activities. A diversity in vegetation and cultural management practices may promote and maintain alternative hosts where the biological control agent may survive and multiply during intercrop seasons or when populations of the main target host have been reduced below a threshold. Where inoculative or inundative releases of the biological control agents are warranted, proper application technology will be needed.

All these points have been addressed in the following subsections, with appropriate examples, discussions, and specific recommendations. Certainly, many other aspects are important to the success of biological control programs. However, all of them cannot be considered here.

RECOMMENDATIONS

1. Establish a national biological control organization. This organization will coordinate all aspects of biological control research such as screening proposals for foreign surveys, making recommendations on biological control matters, evaluating grant proposals, and identifying thrust areas in research. It will also establish cooperation and collaboration between researchers, laboratories, agencies, and governments.
2. Develop a centralized computer data bank to store and retrieve biological control information.
3. Recognize biological control as a major thrust area in agricultural research—not subordinate to other pest management categories.
4. Support all areas of basic research on pests and biological control agents.
5. Fund long-term basic studies on biological control—free from the expectation of a quick pay-off in 5 to 10 years following research initiation.
6. Study propagation and application methodologies for microbials and macrobials.

7. Strengthen studies on genetic improvement of biological control agents, such as developing microbial agents that are amenable to genetic engineering, and determining the impact of genetic variation in founder colonies and in mass rearing and mass release techniques.
8. Expand quarantine facilities and technical personnel to handle quarantine research.
9. Increase user education for handling biological control material.

TECHNOLOGY OF INTRODUCTIONS

Participants first determined that "introduction" included (1) inoculation, (2) augmentation, and (3) inundation. The workshop then set out to identify the technology of placing an antagonist into an ecosystem where it would be effective against a target organism. A question was raised regarding approaches that needed to be studied that would lead to successful introduction of an antagonist to control a target organism. This question was regarded as pre-introduction technology and was not pursued, although pre-and post-introduction technologies cannot always be separated from the technology of introduction. Five priority areas of research were then discussed.

TIMING OF APPLICATION

For biological control to succeed, research is needed to ascertain when applications will be effective. For example, antagonists must be applied to roots of stone fruit trees at a certain time to prevent crown gall; bacteriocins must be applied to blossoms at a specific time to prevent fireblight of apples and pears. More needs to be known of the best time to apply antagonists to control, for example, pruning wound infections by fungi or to destroy populations of northern-joint vetch in a rice field. Other specific needs are determining the most effective time to control thistle weevil, to ascertain the *Colias* predator-prey ratios, and to use *B.t.* These examples illustrate areas where the time of application is crucial to the effectiveness of biological control.

PRODUCTION OF INOCULUM

Research in the mass rearing of insects and in the culture of antagonists is essential to controlling parasites, pathogens, or predators. Some methods involve fermentation processes with liquid media and some involve solid substrates for producing insects or microbes. Work is needed with *Trichogramma* as a parasite of *Autographa*. Choice of media and its ingredients for inoculum production is critical. Another important area is developing cell cultures for insect viruses.

FORMULATION

Research and development must go into the formulation of antagonists in some delivery systems. Spores made into pellets or granules can be used as a seed or soil treatment. Any antagonist applied to seed or soil has to be applied with a material that will not injure the host or antagonist, but will maintain the viability and longevity of the antagonist. Examples needing formulation studies are baits for applying *B.t.* to control cutworm and materials involving *Chrysopa*, a predator of *Heliothis*, as well as antagonists to control root diseases.

ENVIRONMENTAL EFFECTS

When introduced into an infection court, an antagonist must be in harmony with ecological principles of antagonists and host organisms. Factors such as ultraviolet radiation, temperature, and moisture have to be studied. In the soil, temperature and moisture must be considered as well as pH, pesticides, fertilizers, salts, and tolerance to salts. A host of biotic factors of ecological importance have to be studied, especially for biological control of soil-borne diseases and pests.

GENETIC ENGINEERING

Gene manipulation that will enable organisms to withstand environmental stress should be explored. This technique should be used to increase virulence of parasites, pathogens, insects, or weeds or to increase the antagonism of an organism. Also, the searching behavior of insects as antagonists may be improved by gene changes. Examples of other applications include improving the microbial habitat in vector design, improving

the potency of *B.t.*, and developing pesticide resistance for antagonists.

ADDITIONAL RESEARCH

Stability (or variability) of the antagonist, based to some extent on knowledge of the natural host range of the antagonist, is important, because an antagonist must be effective for a critical period of time over a wide range of conditions. This stability may be related to the biotic environment (other beneficial organisms) and to the basic biology and ecology of the antagonist separately and in mixtures. Stability in the interaction of the antagonist with the target organism is necessary for controlling the target organism.

The niche where control will occur has to be known and its characteristics must relate to the interaction of antagonist(s) and target. The antagonist must be appropriate to the niche, which may be an insect's body or the rhizosphere or phyllosphere of the crop or weed plant.

With some diseases or pests, vectors are involved; this relationship needs to be studied so that the vector and antagonist are compatible. If antagonists are released in mass, or as mixtures of taxa, with or without a vector, the technology of introduction has to be worked out.

Where pesticides are applied, the antagonist must be selected and introduced into the target area so that the pesticide does not harm the antagonist. Both antagonist and pesticide must be applied in effective formulations. Therefore, currently used chemical control practices or any other existing commercial materials must be considered.

SUMMARY

Basic biological and ecological information is needed to establish characteristics of the antagonist, target organism, and the niche to successfully introduce the antagonist at the target organism. Knowledge of fungi, bacteria, viruses, nematodes, and insects, as well as crop plants and weeds, is fundamental to successful application of the antagonist in biological control.

QUARANTINE TECHNOLOGY

As biological control moves into greater dominance in agriculture, quarantine technology must be prepared to handle the increased activity. This workshop addressed the question, "How can the quarantine process be improved?" The items submitted by the participants were segregated into six general categories. (See Appendix G for a prioritized list of items.) In order of importance, they were (1) regulatory, (2) handling, (3) facilities, (4) taxonomy, (5) communication/information, and (6) training.

REGULATORY

The three major areas in this category were (1) developing or refining protocols whereby a candidate species may be safely introduced into a target area, (2) improving communication between researchers and port-of-entry officials, and (3) standardizing federal and state regulations. Items of less importance were developing protocols for possible escapes, refining methods of getting organisms from the port of entry to the quarantine facility (this would include packaging), and developing protocols for non-specific biological control organisms. The discussion on protocols was concerned mostly with alternate hosts, facultative hyperparasites, dispersal, and biotypes.

APHIS should be authorized to regulate the importation of beneficial organisms. APHIS regulations then could be directed legally toward increasing efficiency in the permitting and inspecting processes, in speeding the delivery of shipments to quarantine facilities, and especially in standardizing federal and state regulations.

Special labels for biological control organisms are highly important for handling and delivery, as is the need for APHIS inspectors to be thoroughly trained in processing the material. Also, in all stages of the importation process, regulations must be flexible to account for precedents involving, perhaps, unique biological control agents. Such flexibility will insure that biological control agents are not damaged or destroyed from prolonged importation red-tape. This, in turn, provides maximum return to the institution and workers who spend time and money in securing the materials.

HANDLING

This category perhaps most closely approaches the subject of quarantine technology—the hands-on processing of imported material. The items of highest priority were screening for host range in the country of origin before importation, developing artificial tests for quarantine use, and increasing research on quality control. Of much less importance were increased screening of agents in quarantine, devising pest controls (i.e., culture contaminants while in quarantine), learning the disposition of entomopathogens, handling unsolicited material, disposing of shipment residue, and improving the manipulation of target and beneficial organisms in breaking diapause.

Plant pathologists and entomologists were most concerned with screening candidate biological control organisms in their place of origin. Quarantine handlers were concerned with the initial processing of imported material: improving methods to deal with pest contol in cultures, including disposition of entomopathogens, unsolicited material, quality control, artificial diets, and breaking diapause in target and beneficial organisms.

FACILITIES

Developing quarantine facilities in areas where escape of biological control agents would pose no problem and expanding quarantine facilities and support personnel were the two major concerns in this section. There is an urgent need to develop criteria for designing facilities and to train personnel of all levels. Centralizing quarantine facilities in areas where escape presents minimal risk would be ideal, but may be impractical. Perhaps creating primary and secondary quarantine facilities would be more workable.

TAXONOMY

Although the performance of a biological control organism is more important than a formal name, taxonomy at all levels of host-antagonist relationships is vital. Taxonomy and biosystematics, therefore, must have increased support.

COMMUNICATION/INFORMATION

The item of most importance in this category was developing a computerized central communication system. The usefulness of such a system was unquestioned. A separate issue revolved around the need for better communication among quarantine personnel, especially for updates on improved techniques.

TRAINING

Although this category dealt mostly with the quarantine worker at the receiving laboratory, there is a clear need to continue to upgrade the workers through improved training and periodic workshops. Scientists also need more education in handling and shipping biological control organisms.

FOREIGN EXPLORATION

Foreign exploration and the importation of arthropod and pathogenic natural enemies is fundamental to biological control. For this discussion foreign exploration and importation were defined as the processes involved in obtaining arthropod and pathogenic natural enemies from a field environment to combat organisms considered pests in a host country.

The principal obstacles for enhancing foreign exploration at the institutional level was discussed in this workshop. The substantial costs and long-term needs required for foreign exploration, in terms of trained personnel and physical facilities, dictate that these programs not only be supported at an institution, as a minimum unit, but that institutions collaborate to pursue common goals.

We believe that the principal limitations to more effective foreign exploration programs are logistic. These include problems of political or administrative accessibility (not physical) to countries and specific localities, as well as obstacles in export and import clearances, and in rapid shipment. Several serious deficiencies exist in the scientific aspects of the programs, but all depend or are initially limited in some way by logistics.

A major research deficiency is founder colonies—how many individuals are essential for success. Few research studies have dealt with this problem. But until logistical obstacles (as mentioned above) are overcome, a

strong research effort will not clarify the question of how to successfully establish natural enemies with small founder colonies.

Another serious research deficiency is the attitude among scientists identifying economic problems using "species" criteria. Potential biological differences among conspecific populations are frequently ignored. In the real world, however, the immediate cause of a problem is usually related to a population occurring during a defined time and place. Such populations (biotypes) frequently behave differently from other populations that may be similar morphologically but exist in other locations and possess different biological attributes. Studies on genetic and behavioral components of discrete populations are needed for pests and natural enemies.

The USDA maintains four overseas laboratories where some foreign exploratory work occurs: Rome, Italy; Paris, France; Buenos Aires, Argentina; and Seoul, Korea. All are entomology-oriented, but work on pathogens and nematodes may be possible in these laboratories. USDA and SAES (state agricultural experiment station) scientists may work through these laboratories to conduct surveys.

A major problem with foreign surveys is that granting agencies and administrators often do not understand the importance of foreign surveys to biological control efforts. Delays in shipping and clearance of biological control agents are detrimental to the survival of the agents—resulting in wasted research efforts. Surveys in certain foreign locations are difficult for social, economic, or political reasons, and the time and distance involved in surveys and survey strategies is cumbersome.

RESEARCH NEEDS

The question addressed in this workshop was "What is needed in foreign exploration to increase the effectiveness of biological control research?" The researchable needs generated by the group (see Appendix H for listing) were grouped and prioritized. Six areas received top priority: (1) basic ecology studies, (2) cooperation and coordination, (3) biotypes, (4) search sites, (5) computer data base, and (6) administrative support.

BASIC ECOLOGY STUDIES

Researchable topics under this category included, in the order of priority: (1) determining the center of origin of the target pest, (2) field assessment of the control value of biological control agents, (3) determining worldwide distribution of natural enemies, (4) evaluating species complexes in country of origin, and (5) conducting minimal ecological studies in the area of origin. These studies are aimed at understanding the biological control agents in their native country of origin. However, before these studies begin, the correct or most probable country of origin of the target pest must be identified. Although useful biological control agents may be found in other areas, the centers of origin are of primary importance. The center of origin of a target pest may be determined from published accounts of flora and fauna available in libraries. An extensive literature search is, therefore, a prelude to foreign surveys. In some instances, new foreign surveys may be necessary to confirm older records or where information is sketchy.

COOPERATION AND COORDINATION

The important needs in this category were listed as (1) host country cooperation, (2) technical support staff in areas of search throughout the seasons, (3) foreign administrative clearances, cooperation, and reciprocity of exchanges, (4) coordination of exploring groups, and (5) inter-governmental biological control network. The difficulties of establishing good foreign contacts, both in governments and among scientists and technical personnel for accomplishing the goals of explorations were discussed. Other problems concern politically antagonistic countries and countries with specific regulatory laws that constrain the search and export of natural enemies. Social and economic bottlenecks in several regions of the world also hinder biological control exploration. Therefore, establishing and strengthening cooperation with foreign countries should be among the first steps taken to promote foreign exploration.

The availability of local technical support personnel who are knowledgeable about the scientific aspects of a survey, as well as the local people, language, regulations, and geography, is vital to the success of foreign explorations. It may be impossible to survey many regions of the world without local technical help. While funds to hire foreign technical support personnel may be generated through grants and PL-480-type monies, their

availability, especially on a yearly or a continuing basis, could be a problem. Perhaps a governmental or inter-government biological control network can deal best with this problem.

BIOTYPE STUDIES

The research needs were prioritized as (1) determining the pest biotype and (2) determining and choosing the natural enemy biotype. "Biotype" can have different meanings. Any biological type is a biotype. Specifically, it could be a pesticide-resistant type, a certain morphotype, an ecotype, and so on. Nonetheless, the variability of the pest and the natural enemy is of great concern for successful biological control. The correct type of pest and the right type of natural enemy must be identified; otherwise, biological control efforts will be misdirected.

Biotypes can be studied by different means, depending on the characteristics of the types. For example, pesticide-resistant biotypes may be identified and screened for pesticide tolerance/susceptibility by biochemically changing the pesticide or pesticide concentration.

SEARCH SITES

Priority areas in this category were (1) searching in ecologically homologous areas, (2) search and sampling strategies, and (3) diversity in acquiring natural enemy sites. Selecting sites that most likely will yield promising natural enemies is vital to successful biological control. Whether the sites are in the center of origin of the target pest or in other geographic areas, proper selection is important to judiciously allocate funds, time, and personnel. But the choice of sites may be determined by the pest-natural enemy biology. For example, emphasis may be placed on ecologically homologous areas, climatically comparable areas, and/or areas where the pest density is low, perhaps due to the prevalence of natural enemies.

COMPUTER DATA BASE

The USDA is developing a computerized information retrieval system for biological control agents introduced into the United States. Natural enemies of major pests in major crops, attempted biological control programs, and other data on previous biological control introductions to determine how the natural enemies performed are examples of information that could be stored. Such a computerized data base could serve research, teaching, regulation, and planning. More importantly, it would save time and effort by efficiently providing biological control information.

ADMINISTRATIVE SUPPORT

Administrative recognition of the need for support for foreign exploration, sources of funding, and a list of biological control targets were priority items in this category. Administrators do not seem to recognize the need for funding foreign explorations—perhaps because certain administrative and institutional levels do not appreciate the value and seriousness of foreign explorations. Funding for foreign travels, consequently, is difficult to obtain. One solution would be to better inform people at these levels of biological control programs and needs.

RECOMMENDATIONS

In summary, the six high priority needs in foreign exploration can be grouped under research, administrative, and facility categories. These needs may be best met by a national biological control organization, which would be a clearinghouse for grant proposals, would screen proposals for foreign surveys, make recommendations, and identify thrust areas in biological control research. Also, this organization could identify researchers and laboratories for specific biological control and related research. In addition, biological control should be an independent, main research area under Agriculture—not subordinated to any other category.

Specific Recommendations

1. Establish a national biological control organization that will include:
   a. a central computer with data on all aspects of biological control;
   b. an administrative coordinating committee of active scientists, not administrators, to coordinate live specimen and information exchange among participants (federal and state research and regulatory units and private insectaries); and
   c. a coordinating committee of active scientists, not administrators, to periodically reevaluate research priorities, and participate in evaluating competitive grant proposals.

2. Through the U.S. National Biological Control Organization, collaborate with OIBC, CIBC, AID, and FAO to establish an international network for biological control, including:
   a. coordinating all information exchange via a central computer bank in the U.S., and
   b. establishing protocols among member governments to facilitate travel, exploration, shipments, and live materials and information exchange.

INCREASING ABUNDANCE AND EFFECTIVENESS

Most agroecosystems are so disrupted by cultivation and chemical applications that biological agents such as microbials, antagonists, predators, and parasitoids become separated from their competitors, hosts, or prey (pests) in either space or time. This lack of connection or synchronization often leads to crop damage because the pests are not being regulated by their enemies or competitors. This "too little, too late" syndrome may be corrected by increasing or enhancing the abundance or effectiveness of various biological control agents—a tactic that will be used more as the technology of manipulating biological control agents advances. The advantages of exploiting biological control agents are selectivity of control (not disrupting or harming non-target organisms, including humans) and reduced incidence of resistance to the control agent.

This workshop addressed the question of "What approaches might be used to enhance the abundance and effectiveness of biological control agents?" The topic was divided into three areas: (1) chemical, nutritional, or physical manipulation; (2) vegetation and cultural management; and (3) propagation and release or application. The participants then broke into groups for separate discussion of these areas.

CHEMICAL, NUTRITIONAL, OR PHYSICAL MANIPULATIONS

Overview

Although the interactions are more hidden and subtle among microorganisms than insects, more plant pathologists than entomologists use chemicals, including nutritional chemicals, and manipulate the physical environment to increase the effectiveness of biological control agents. Dr. Baker, in his introductory talk, showed that a single element, like iron, can determine whether or not a disease occurs. Chemical secretions (antibiotics) of certain microorganisms can make the soil suppressive, and the amount of nitrogen in the soil positively or negatively influences certain crops--depending on the microorganisms. The chemical composition of the soil more directly effects beneficial and harmful microorganisms than soil insects. Furthermore, changes in pH, the use of certain fertilizers, and irrigation practices influence soil microorganisms much more directly than insects. Therefore, the use of chemicals and the manipulation of the physical environment is of greater importance today to plant pathologists than entomologists, but there is also a future for manipulating beneficial insects with chemicals.

The use of chemicals to increase the effectiveness of entomophagous insects is in its infancy. The few chemicals employed influence behavior, particularly the searching behavior of predators and parasitoids. Many entomophagous insects respond to a series of chemical cues that ultimately lead them to their prey or hosts. First, entomophagous insects are attracted to volatile chemicals originating from the host plants of phytophagous insects. The parasitoid narrows in on the phytophagous insect host by following chemical odors emanating from (1) the feeding site (such chemicals may be produced by the interaction of the phytophagous insects' salivary secretions with the wounded leaf tissues), or (2) the feces of the phytophagous insects, or (3) host insects.

The actual use of behavioral chemicals to increase the effectiveness of entomophagous insects is still experimental. For example, W. Joe Lewis, USDA Lab at Tifton, Georgia, has made some progress toward increasing *Trichogramma* parasitization of moth eggs by applying a hexane extract of most scales to crop leaf surfaces. When *Trichogramma* contact the extract, their searching behavior changes from random movements to a search for host eggs.

K. S. Hagen, (University of California--

Berkeley) has used behavioral chemicals (kairomones) and nutritional chemicals to attract green lacewings, *Chrysopa carnea*, to stimulate feeding on artificial food and to produce and deposit eggs. Adult lacewings fly with the wind in the evening until they sense a volatile chemical coming from oxidized tryptophan (indole acetaldehyde) plus a volatile chemical signalling the presence of plants. Upon receiving these volatiles (kairomones), the *Chrysopa* turns and flies into the wind, landing frequently until it locates the source of the "tryptophan," which is in honeydew. Honeydew is the adult's natural food. With artificial honeydew, which simulates the presence of a high aphid population, chrysopids lay eggs earlier than normal. This then leads to an earlier population of chrysopid larvae, which are general predators, before the pest populations reach economic injury levels.

Response to the Question

This group divided its question into two areas: (1) chemical and nutritional manipulations, and (2) physical manipulations. The ideas generated for the chemical and nutritional manipulations for increasing the effectiveness of biological control agents fell into five categories: formulating or manipulating agents, combining chemicals to affect host resistance or to enhance agent activity, altering nutrition of host to favor biological control agent, altering nutrition of agent to affect efficiency, and habitat management. (See Appendix I-1 for list of ideas and examples.)

As seen in Appendix I-1, there are many ways of increasing the effectiveness of biological control agents with chemicals or by manipulating the nutrition of the host or the agent. However, more basic studies of chemical and nutritional influences on antagonists, mycoparasites, and entomophagous insects will point to new ways of increasing the effectiveness.

Most of the ideas on physical manipulation come from plant pathologists (see Appendix I-2), although most implied the manipulation of entomophagous insects. Specific cultural practices can control certain pests by improving the environment of the antagonist or mycoparasite. From the discussion, soil is clearly the main environment that can be manipulated, more specifically through soil tillage, irrigation, compaction, drainage, and crop residue management.

VEGETATION AND CULTURAL MANAGEMENT

Overview

Large-scale crop monocultures often seriously affect the abundance and effectiveness of resident and introduced biological control agents, which depend on habitat complexity for alternate prey/hosts, pollen and nectar, shelter, nesting, and overwintering sites. Diversifying the agroecosystems within and around a field increases the environmental opportunities for natural enemies and, consequently, improves biological pest control. A classic case is that of the egg parasitoid wasp *Anagrus epos* which more effectively controls grape leafhopper, *Erythroneura elegpantula*, when wild blackberry (*Rubus* sp.) plants grow near vineyards. The wild blackberry leafhopper, *Dikrella cruentata*, is an alternate food for the parasitoid.

Russian researchers found that aphids, scales, and other orchard pests had a higher incidence of parasitism when more honey plants (i.e., *Phacelia* and *Eryngium*) were planted in orchards. In Canada, wild flowers in apple orchards resulted in an 18-fold increase in parasitism of tent caterpillar pupae, and 5-fold increases in codling moth larvae parasitism.

In Hawaii, sugarcane weevil parasite, *Lixophaga shenophori*, populations increased when nectar-source plants were planted in sugarcane field margins—up to a distance of 60 meters from the borders. Researchers in California, New York, and the tropics have documented biological control in polyculture cropping systems.

The activity of biological control agents is enhanced when cultural practices, fertilization regimes, weed management, row spacing, crop rotations, etc., are modified in an agronomic and ecologically compatible manner. In Georgia, for example, populations of the velvet bean caterpillar and of the southern green stink bug were higher in weed-free soybean fields than in soybean fields left weedy for two or four weeks after emergence.

Response to the Question

This group addressed the question of "What approaches might be used to enhance the abundance and effectiveness of biological control agents by vegetation management

and cultural management?" Before generating ideas, the group defined three major approaches.

1. Design cropping systems that will lead to well-established biological control relationships. This includes intercropping to provide alternate hosts and adding non-crop plants to support natural enemies.
2. Develop agronomic management techniques that enhance natural enemies. This includes fertilization regimes that alter plant components, row spacings, and rotations.
3. Study nutritional manipulations, including the addition of a food base along with antagonists.

Of the ideas generated (see Appendix I-3), the five areas of highest priority were (1) determine the effects of environmental and ecological factors on the biology of the biological control agent; (2) conduct detailed floristic and formal surveys to know what plants and animals are in the agroecosystems; (3) develop and study how vegetation management techniques, such as crop rotations, fertilization, and reseeding affect biological control agents, and determine the socio-economic benefits of manipulations; (4) conduct basic biological studies on the seasonal cycles of biological control agents; and (5) determine seasonal sources and measurements of biological control agents. To fulfill these research needs more scientists will need training in agronomy, ecology, and pest management.

PROPAGATION AND RELEASE

Overview

For plant pathologists, applying the inocula of biological control agents in or on infection courts offers the greatest potential for success. Although the time when plants can be protected from disease is relatively short, the inoculum for control is manageable. Agents can be included in planting equipment, coated on seeds, or applied during wounding. The few examples of successful biological control in plant pathology include controlling (1) seedling diseases by seed treatment and (2) wound pathogens by applying biological control agents. Pathogens on blossoms may be controlled by the timely application of biological control agents. Research on soil-borne diseases, where natural soil suppressiveness has been identified, also show great promise for biological control.

Entomologists see great potential for increasing the effectiveness of biological control agents by using propagation and timed releases. For example, if naturally occurring entomophages (predators and parasites) cannot control a pest, their numbers can be increased by propagation and release. Methods have been developed for large-scale propagation of a number of predators and parasites, and some of these are used throughout the world for managing pest arthropods. Most commonly, entomophages are released to immediately control pest increase and damage, yet releases can be timed to control subsequent pest generations. This approach can be cost effective, is a renewable resource, and has none of the problems associated with insecticides (e.g., detrimental impact on non-target organisms, development of resistance, and elevation of other arthropods to pest status).

Response to the Question

Of the ideas generated (see Appendix I-4), six were given priority. Research to genetically improve biological control agents was most important. Both pro and eukaryotic natural enemies, for example, could be genetically improved. This would involve standard breeding techniques and high technology gene transfer. Different biological control agents offer different levels of opportunity at this time because of the available information. The limiting factor is that sometimes positive biological control attributes cannot be improved.

The conditions necessary for producing effective biological control agents *in vitro*, *in vivo*, and *in situ* are also important. Currently, most laboratories can only produce small amounts of microbial agents, which usually are not sufficient for most test plots. Different cultural conditions (fermentation processes) need to be elucidated for each microbial agent.

Also, augmenting entomophagous arthropods with periodic releases often is limited by the cost of producing high quality agents. *In vitro* rearing techniques, however, might be able to mass produce a standardized product at a competitive cost.

How environmental and cultural practices affect biological control agents also needs to be researched. For example, how do basic atmospheric and edaphic (soil) conditions influence the effectiveness of the bio-

logical control agent(s)? What effects do cultural practices, at different stages of crop (or animal host) development, have on biological control agents? Detailed population studies of the crop (or animal host) pest status in the absence of the biological agent treatment in check areas need to be conducted to answer these questions.

More information is needed on the biology of biological control agents. The probability of successes is enhanced with each improvement in biological data available at the time of release and/or manipulation. These data include behavioral, ecological, dispersal patterns, diapause, or dormancy reactions to various media. Research should be started in the native home of the biological agent and continued until well after field releases. All pertinent data needs to be supplied to the people attempting field releases and dispersals.

The effectiveness of a given biological control population could be influenced at the time of release or application by (1) other natural enemies already in the field, (2) density-independent factors such as weather, and (3) pest phenology. Thus, research is needed to identify the optimum timing and optimum pest/biological control agent ratio. Studies are needed to determine the best time to release microorganisms so that they coincide with factors most favorable for that organism to be effective. The time that an organism appears as a biological control agent under natural conditions may not be the same as the time the organism is most effective as a biological control agent.

Biotypes of strains of both pest and natural enemy markedly influence biological control. Strains of natural enemies may have differences in host specificity (within a host population or populations), and subtle differences in behavior or genetic resistances may affect the efficacy of biological control. Understanding the diversity existing within target and biological control agent populations will be valuable for improved collection and use of biological control agents.

Section Chairpeople

L. A. Falcon
Entomology & Parasitology
University of California
Berkeley

I. J. Misaghi
Plant Pathology
University of Arizona

Workshop Leaders

Induced and Natural Epidemics

L. P. Kish
Entomology
University of Idaho

D. O. TeBeest
Plant Pathology
University of Arkansas

Microbial Agents

I. J. Misaghi
Plant Pathology
University of Arizona

L. A. Falcon
Entomology & Parasitology
University of California
Berkeley

Microbial Registration

R. H. Kupelian
IR-4 Program
Rutgers University

W. L. Biehn
Office of IR-4
Rutgers University

D. M. Baker
IR-4 Headquarters
Rutgers University

M. E. Burt
IR-4 Headquarters
Rutgers University

K. Dorschner
2612 Lakevale Drive
Vienna, VA 22180

J. E. Elson
IR-4 Headquarters
Rutgers University

R. T. Guest
IR-4 Headquarters
Rutgers University

G. M. Markle
IR-4 Headquarters
Rutgers University

PROBLEMS AND OPPORTUNITIES

OVERVIEW

In recent years research activities and developments in biological control have been expanding rapidly. Generally, scientists working with biological control agents have stayed within their disciplines. At this conference, plant pathologists, entomologists, and weed scientists working together reduced the isolation and lack of communication that exists between workers in these areas.

The microbial agents workshop focused on four problem areas common to all groups: detection, production, application, and evaluation. Surveillance and detection produce much of the raw materials needed to develop biological control agents. The discovery of new species, subspecies, and strains, provides material that may supplement, extend, or replace existing agents. Also, it broadens our understanding of the ecosystems involved and provides materials that may be of value to genetic engineering. There is a great need to organize, finance, and execute exploration projects on the local, regional, and national levels. These efforts should focus on surveying and detecting biological control agents on all stages of plant growth and at all levels of crop-host interactions

The production of antagonists for research and commercial purposes faces many challenges. However, a disproportionately small amount of research has gone into this area. Eventually, efficient, automated, mass culture systems will be needed to provide biological control agents of high quality, purity, and efficacy at a reasonable cost. Only in this manner will the industrialization of biological control agents for pest control be achieved.

Disseminating biological control agents ranges from simple, routine methods to highly complex, involved systems. Researchers commonly use "available" systems, which often have been developed for other purposes and do not provide the desired results. The parameters and equipment used can be equally important in determining the success of application. Biologists can benefit from interactions with engineers and computer scientists in these endeavors.

The outcome of the evaluation of microbial agents for biological control provides the justification to continue, refine, or abandon a project. The correct decisions can be made only with the proper tools and techniques.

The induced and natural epidemics workshop felt that a better understanding of dynamic interaction was necessary to emphasize environmental and host resistant factors, predator-parasite-antagonist relationships, development of new techniques, identification and characterization of pathogens, and modeling and management. The influence of environmental factors on epidemics should progress using field observations and interdisciplinary computer simulations. Studies related to the host should include mechanisms of resistance and susceptibility, the effect of host and host microflora on parasites and antagonists, and genetic diversity of the target host at the community and ecosystem level.

More information is needed on the mass production of predators, parasites, and antagonists; enhancement of their activities; and the compatibility of biological control agents with other biotic agents and with agricultural chemicals. Techniques should be developed to identify, characterize, and monitor biological control agents. To expedite these objectives, multidisciplinary taxonomy and reference resource centers should be established. The predictive capabilities of modeling systems should go into on-line management programs. Such on-line management programs could assess performance of developed strategies, also.

Upon reaching a level of success with a biological control agent, industrialization and commercialization may be desirable. Registration with the EPA may be necessary before this can happen. If the candidate biological control agent has limited importance, or a minor use, the cost needed for developing the required data may not justify involvement of private firms.

The IR-4 is a national agricultural program that was created to help obtain clearances for chemical pesticides for minor or special uses. Recently it was expanded to include biorational pesticides for use in pest management systems. This program has provided a boost to biological control efforts.

Through its involvement, more attention and support for developing and registering biological control agents is anticipated.

RECOMMENDATIONS

1. Encourage greater cooperation among disciplines through administrative reorganization and regional and national meetings.
2. Establish and maintain surveillance, detection, and exploration programs for beneficial microbial agents.
3. Improve instrumentation for continuous remote sensing of the micro-environment.
4. Increase and expand biological control agents production research, including genetic engineering technology, and develop procedures to produce microbial agents at a reasonable cost.
5. Improve application technology by soliciting inputs from soil scientists, plant physiologists, biochemists, physicists, microbiologists, and statisticians.
6. Develop techniques for monitoring genetic shifts in biological control agent and target populations.
7. Establish taxonomy and reference resource centers for biological control agents.
8. Provide the IR-4 program with funding to enhance its ability to research and develop registration information for biological control agents.

MICROBIAL AGENTS

Beneficial microbial agents (fungi, bacteria and rickettsia, protozoa, and viruses) capable of interfering with the destructive activities of plant pathogens, insects, and weeds are being intensively studied by plant pathologists, entomologists, and weed scientists interested in non-chemical controls for plant pests. Although the potential of these organisms to control plant pests is great, scientists have touched only the surface of their capabilities. The search for beneficial microbial agents is justified further by the ever-increasing cost of chemicals, which currently are used almost exclusively to control pathogens, insects, and weeds. Agriculture can only benefit from having a larger resource of microbial agents that can be used in the field.

The purpose of this workshop was to stimulate new thoughts in researching and developing microbial agents for the biological control of pests and diseases in crop production. The terms "antagonists" and "microbial agents for biological control" are used interchangeably.

Ideas generated in the workshop (see Appendix J) were divided into four categories—detection, production, application, and evaluation—to facilitate discussion. A summary of these deliberations follows.

DETECTION

The major drawback to developing microbial agents for biological control was considered to be the lack of methodology for detecting useful microorganisms. Therefore, new methods to identify microbial agents should have top priority. Survival is another problem. Because microbial agents are more likely to survive in their native environment, the search for microbial agents should start in the locations where they will be reintroduced. Other important points are the nature of interactions among antagonists, multiple strains versus single strain for biological control and dependability and appropriateness of field tests. Laboratory or greenhouse conditions should mimic field conditions. *In vitro* screening of antagonists by antibiotic production was criticized. This is because antagonism can be due to mechanisms other than antibiosis, and selections based solely on antibiotic productions can eliminate useful antagonists. Therefore, microbial agents should be screened by their predictive modes of action.

PRODUCTION

The basic problems facing production technology is a paucity of basic information and the lack of collaboration among individuals and institutions involved with biological control. Basic information should originate with research directed at microbial mutation, quality assurance, production technology, and the value of single versus multiple microbial

agents. Mutation of microorganisms is a major stumbling block for achieving homogeneity of biotic agents and their products. Procedures, like simulation modeling, should be developed to identify and monitor mutation and microbial activities. The potential of genetic transfer in the field should be evaluated, also. However, controlled mutations through mutation technology could produce mutants with desirable traits.

To improve quality assurance, units should be standardized. Reproducible field bioassays, thresholds of microbial contamination, and sampling procedures should be developed, and the effects of the environment on biotic agents needs to be researched.

APPLICATION

The considerations of and, to some extent, procedures for microbial control of plant pathogens or insect pests are similar. With the available technologies, scientists should rapidly develop microbial agents for crop protection. The quality of the antagonist inoculum is most important, followed by application technology. Antagonist effectiveness should be improved by synchronizing application with the population dynamics of the antagonist and the target to (1) strike the target during its most susceptible stage and (2) overcome the vigor or resilience of the host to the antagonist. Also, we must understand how agronomic and agricultural practices effect (1) the susceptibility of the host to an antagonist, (2) the condition and properties of the target food source, and (3) the application of other agents. The latter includes herbicides, insecticides, and fungicides. For application technology, we need to better understand existing application equipment or develop more effective equipment. Other areas concern the plant's effect on antagonist activity, such as exudates and other chemical substances produced by the plant, and on the susceptibility of the target. Maintaining the virulence and the quality of the antagonist before use (in storage), during application, and on the target (residual effectiveness) also needs to be researched. Formulation and tank mix; dose, volume, placement and timing; crop or cultivar; environmental factors; and agronomic factors are other areas that should be considered when studying application technology.

EVALUATION

Although a number of issues were identified, the major concern was understanding how the environment affects the efficacy and usefulness of the antagonist. The next most important issues dealt with understanding the effects (1) of the environment on the durability and persistence of the antagonist at the target site, (2) of population dynamics of the target and host plant on the effectiveness of microbial antagonists, and (3) of agricultural chemicals on antagonist activity.

Increasing dependability and usefulness of field study methods was discussed, also. Genetic diversity must be maintained in laboratory cultures that will be used in the field. Although this is sometimes incompatible with other research goals (i.e., strain selection), it must be emphasized wherever possible. Standardized procedures should be used, particularly when evaluating interactions among antagonists, targets, and agricultural chemicals. The availability of these procedures is widely recognized and their use needs to be emphasized more heavily.

Progress in biological control using microbial agents will be linked to the following.

1. Instrumentation for continuous sampling and remote sensing of the microenvironment should be improved. Environmental parameters that require monitoring at this level include moisture, temperature, pH, light (especially UV), and wind. Trained personnel, needed for instrumentation development, include engineers, soil scientists, biochemists, and physicists.
2. Bioassay techniques to assess antagonist durability and monitor population effectiveness must be improved. Mechanisms of action and biochemical markers need to be identified so that more sophisticated techniques can be developed.
3. Techniques of monitoring genetic shifts in antagonist and target populations over time and space need to be incorporated into population dynamics studies. Modeling technology also must be included in such studies and will require individuals formally trained in this technology. Unfortunately, the availability of experienced individuals in this area is low.
4. Statistical techniques to assess the reli-

ability of the various field testing methods must be improved. This will require help from statisticians.

SUMMARY

The future of beneficial microbial agents is bright. Current technologies should allow scientists involved in microbial research to make rapid progress toward developing effective methods for biological control. Increased collaboration between scientists in the different disciplines involved in this field will facilitate progress, as will the development of universally accepted definitions and terms.

NATURAL AND INDUCED EPIDEMICS

Natural and induced pathogen-host associations form the basis of efforts to manipulate environmental resistance expressed as disease-induced mortality. Biological control of insect and plant pests by microbial organisms is a naturally occurring phenomenon that must be understood in all its dynamic interactions before it can be practically implemented into forest and agricultural pest control programs. Historically, suppressing pest populations with pathogens has been ineffective, because scientists did not understand fully the complex driving mechanisms involved, particularly those of the physical environment.

The large scale use of pesticides, which may pollute the environment, select for resistant target organisms, kill non-target organisms, and have become progressively less economical, has provided the impetus for serious research efforts to control noxious insects and plants with naturally occurring pathogens. Consequently, a thorough understanding of epiphytotic and epizootic relationships is of paramount importance for developing organisms such as controls.

Although plant, and more recently insect, pathogen models predict population dynamics, they have been developed for only a few pest-pathogen systems. Virtually nothing is known epidemiologically for the majority of naturally occurring pathogens of insects and plants. Pest control efforts by entomologists and plant pathologists have been undertaken largely in ignorance and isolation from each other. Often, individual efforts within each discipline are ineffective or antagonistic to those of the other discipline.

To address problems of mutual interest and importance to plant and insect pathologists, participants in this workshop identified six research areas common to both insect and plant pest control: environmental factors; host resistance factors; predators, parasites, and antagonists; techniques, identification, and characterization of pathogens; and modeling and management.

Researchable problems within each of these six research areas were discussed and prioritized to identify mutual problems and concerns and the methodology, resource requirements, and cooperation necessary for solution. Discussion of each problem, expressed as a subobjective to the researchable area, follows.

ENVIRONMENTAL FACTORS

The five researchable objectives identified were (1) physical and biotic environment, (2) affects of climatic factors on maintaining epidemics, (3) post epizootic and epiphytotic population dynamics, (4) strain selection, and (5) long-distance dissemination of microbials. Methods developed to achieve these objectives should include field observation methodology, computer simulation studies, and administrative restructuring that would foster interdisciplinary cooperation. Additionally, regional meeting participation by consultants from other disciplines, cooperative research among disciplines, and a forum for reporting cross-discipline research would help achieve the objectives.

HOST RESISTANCE FACTORS

A host may be the target of a microbial control agent or a host crop needing protection from a pest, insect, or pathogen. The host crop and the target host influence predation, parasitism, or antagonism by a biological control agent.

Major research areas related to the target host include: (1) mechanisms of resistance or susceptibility at the organismal level, including immunity and nutrition; (2) the influence of host microflora on biological

control agents; and (3) genetic diversity of the target host at the community and ecosystem level. Research related to the host crop include: (1) the effect of the host crop on survival and activity of predators, parasites, and/or antagonists of crop pests; and (2) the influence of host crops on pests.

Both analytical and bioassay techniques are needed to study the physiological basis for susceptibility of target hosts to parasites, predators, and antagonists. Techniques including methods of monitoring population dynamics of crop hosts, target hosts, and biological control agents must be developed.

PREDATORS, PARASITES, AND ANTAGONISTS

Three main objectives were identified within this study area, each with several subobjectives.

Enhancement: (1) increasing or decreasing the activity or virulence of pathogens, predators, or antagonists; (2) manipulating host range specificities of pathogens, predators, or antagonists; and (3) developing techniques to validate the genetic stability of pathogens added to an environment relative to potential recombination with those already present.

Mass production of biocontrol agents: (1) formulation and *in vitro* techniques; and (2) genetic manipulation of pathogens to improve commercial formulation potential, shelf-life, field activity, and other factors of economic importance.

Compatibility studies of biological control agents with other biological control agents, chemicals such as fungicides, insecticides and herbicides, and management practices associated with crop production are needed.

Methods for enhancing pathogenicity through field selection, genetic manipulation through mutation, mating, etc. are fairly well understood. However, little expertise is available for biological engineering or genetic recombination studies with filamentous fungi. There is a major need to validate the genetic stability of these organisms. Methods are needed for deep liquid fermentation, solid state fermentation, production of viruses in cell tissue culture, and *in vitro* culture of obligate parasites.

TECHNIQUES, IDENTIFICATION, AND CHARACTERIZATION

Two categories of research, neither of which was more important than the other, were identified: (1) detection and measurement and (2) induction. Research in detecting and measuring natural and induced epidemics falls into two subcategories. Under the first subcategory, research should be multidisciplinary and should be concerned with developing and refining biochemical/immunological methods, developing clinical techniques, establishing taxonomy centers for biological control agents, developing reference resource centers, improving soil pathogen propagule detection methods, emphasizing host range studies, and developing methods to detect bacterial toxins on host plants. In the second subcategory, monitoring techniques, research should be devoted to improving and standardizing sampling techniques and data management, developing prediction thresholds, and developing biological markers, remote sensing, and field sampling kits.

Research in the induction category should be directed toward improving bioassay methods, increasing the survival and virulence potential of microbial agents, searching for genetic basis of induction, studying the model method of disease transmission, refining mass production methods including *in vitro* techniques for fastidious organisms, improving application technology, developing *in vitro* methods to predict microbial interactions, and studying the effects of nutritional quality of host plants and other interacting factors.

MODELING AND MANAGEMENT

The similarities, rather than the differences, between host-pathogen systems need to be identified to allow the information to be used by scientists in different disciplines. The best way to do this might be with computer-based information systems.

Modeling and systems analysis will further the science of host-pathogen systems already targeted for study by individual regional projects. The models must be used in online pest management programs and as predictive tools to evaluate potential management tactics. Large area (interregional) performance and economic evaluation strate-

gies, tactics, and models should be done in inter-regional projects.

To coordinate model development, each regional project involved with, or potentially incorporating, microbials as biological control agents should appoint a modeling coordinator. The modeling coordinator would organize modeling activity in a project and would meet annually with other coordinators to report on and compare modeling activities in their projects. The annual meeting would ensure rapid incorporation of new technology throughout the microbial biological control community.

Existing models should be evaluated for their similarity, availability, and potential utility. A few exemplary systems should be highlighted at introductory coordination meetings. This would help other modelers resolve problems in epidemic modeling, obtain data needed in their respective projects, and coordinate empirical research for model parameterization.

Evaluation and validation of model performance can be executed within the individual regional projects over large areas. The modeling coordinators would then facilitate the models being integrated into existing management systems, since each coordinator would probably be associated with one or more management system external to the regional project system.

SUMMARY

Natural or induced epidemics are the basis for microbial biological control. Each epidemic is governed by physical and biotic environmental factors. Therefore, practical and efficient use of microbial agents depends on a thorough working knowledge of the dynamic interaction of the environment with pest-pathogen population dynamics.

Pest control efforts by plant and insect pathologists have been concerned traditionally with controlling damaging insect pest populations and diseases of economic crops. Currently several models predict disease losses in crops and the dynamics of disease incidence in insect populations. However, little information is available on weed diseases and on how the environment effects the biological interactions of hosts and parasites. Few examples have been studied to draw parallels between different groups of pathogens or even between crop diseases and weed diseases. Epizootics among insect populations are difficult to predict because of the nature and number of field parameter assessments that are necessary to make a model practical.

Although the physical environment is probably the most limiting factor for epidemic development, other factors including host variability and biotypes, pathogen variability (biotypes), pesticide interactions on biological control organisms, techniques to measure and identify suitable candidates, and environmental management also must be developed more fully for microbial biological control to be successful. The organisms now being used can only serve as examples and guides for future prospects.

REGISTRATION OF BIORATIONALS INTERREGIONAL RESEARCH PROJECT NO. 4

The IR-4 was established in 1963 by the state agricultural experiment stations and the USDA to provide national leadership, coordination, and focus for obtaining clearances for pesticide uses on minor or specialty crops. The program involves a cooperative effort between the USDA/CSRS, USDA/ARS, SAES, EPA, and the pesticide industry. The need for IR-4 arose, and still exists, because the agricultural chemical industry cannot economically conduct research for control agents with limited market potential. Since 1963, the IR-4 program has funded research to obtain efficacy and residue chemistry data necessary to register pesticides for minor uses; IR-4 also has submitted this information to EPA to obtain tolerances.

The objectives of the IR-4 program have been expanded recently to include the registration of biorationals (biochemicals and microbials) for pest management. In light of this, this workshop dealt with the proposed EPA requirements for registration of biorationals.

Entomologists, plant pathologists, weed scientists, and others participated in this workshop, which was divided into two sections. The first section presented informa-

tion for registering biorationals (Appendix K-1). The second section generated questions from the participants concerning biorationals.

Most questions dealt with the studies, clearances, formulation changes, and other registration needs for biorationals. Questions were raised on whether siderophores, mycorrhizal fungi, soil-existing fungal biological control agents, microorganisms that increase crop growth, and genetically engineered microbial pest control agents needed to be registered and what the requirements would be. Additional questions concerned industry and IR-4: when would industry be involved in registration; did industry need to be involved; when would IR-4 get involved; and how could resources from the USDA, SAES, and industry be used? (Appendix K-3).

BIORATIONALS

Biorational pesticides are inherently different from conventional pesticides. Some of the characteristics of biorationals are their unique mode of action, low use volume, target species specificity, and natural occurrence. EPA expects that many biorationals have lower risks than conventional pesticides, thus, they will be subject to different data requirements (section 158.165 as proposed in the Federal Register Nov. 24, 1982). The two major categories of biorationals are biochemical and microbial.

Biochemical pest control agents must meet two criteria:

1. They must have a mode of action other than direct toxicity in the target pest, such as growth regulation, mating disruption, and attraction. Strychnine, rotenone, nicotine, and pyrethrin are directly toxic and are not biochemical pest control agents, according to the EPA definition.
2. It must be naturally occurring or, if synthetic, it must be structurally identical to a naturally occurring chemical. For a synthetic to be identical in structure, the molecular structures of the major components must be the same as the molecular structures of the naturally occurring analogs. Minor differences in the stereochemical isomer ratios are acceptable. If it contains an inert ingredient that might be hazardous, the data requirements would be the same as for inerts in a conventional pesticide.

Microbial pest control agents include bacteria, fungi, viruses, and protozoans. The data requirements apply to all microbial pest control agents, including those that are naturally occurring and those that are strain-improved. Each variety or subspecies must be tested. Genetically engineered microbials will be examined on a case-by-case basis. Pest control organisms such as insect predators, nematodes, and macroscopic parasites are not considered to be biorational pesticides.

REGISTRATION OF BIORATIONALS

The same laws for registering conventional pesticides apply to biorationals, with some differences in the EPA data requirements. All pesticides of any type must be identified for ingredients and composition. The EPA data requirements for biorationals are used to determine their fate and to evaluate their potential adverse effects to humans and other non-target organisms. These will depend on the kind of use (terrestrial, aquatic, greenhouse, forestry), whether food or nonfood crops will be treated, whether it is a biochemical or microbial pest control agent, on the results of toxicity tests, and on the amount applied per acre. At present, EPA is considering whether to exempt pheromone traps from registration.

PRODUCT CHEMISTRY

The biorational pesticide must be identified by ingredients and composition. There must be a description of the manufacturing process and a discussion of the formation of unintentional ingredients. Physical and chemical properties and methods of assay are required for the manufactured product and the end product—the material that will be provided to the user. Samples may be required.

RESIDUE AND TOXICOLOGY DATA

Residue chemistry data will not be needed for biochemical pest control agent products if the use rate is less than 20 grams active ingredient per acre per application and if the product meets the requirements of Tier I toxicology tests. Residue data for microbial pest control products are not needed if Tier II or Tier III toxicology testing is not needed (Appendix K-2).

If residue data are needed, the first requirement is for an analytical method suit-

able for enforcing a tolerance. This means the method must not require exotic equipment or procedures and must be completed in a relatively short time.

Data on the nature and level of residues in processed food/feed are required when detectable residues could concentrate in processing and thus require a food additive tolerance.

Residue data are needed on food crops representative of the rate, number of applications, preharvest interval, and relevant restrictions. These restrictions may be nonfeeding or grazing conditions for a certain number of days after application. Data on the nature of residues found in plants will be needed and the nature of residue in livestock will be needed if residues are found in feed. Data for residues in meat/milk/poultry/eggs will be required on food uses if the pesticide occurs as a residue in livestock feed. If the application is to an aquatic environment the above tests, plus data for water, fish, and crops that may be irrigated by the treated water will be needed.

CLEARANCES

The IR-4 has provided information such that four biorational pesticides have been registered. The biochemicals registered are gibberellic acid, for use on blueberries and strawberries, and methyl eugenol, for use on all raw agricultural commodities. The microbials registered are *Bacillus popilliae*, for use on pasture and rangeland grasses, and *B. thuringiensis*, for use on all raw agricultural commodities.

ESTABLISHING COOPERATIVE RELATIONSHIPS

ESTABLISHING COOPERATIVE RELATIONSHIPS

Arthur Kelman (Chairman)
University of Wisconsin-Madison

John Lockwood (Co-Chairman)
Michigan State University

A major concern of the participants at the conference was the need to establish new or improved ways to enhance cooperative efforts and strengthen relationships among the scientists from the different disciplines involved in biocontrol research. An ad hoc committee, including representatives of entomology, plant pathology, and weed science, met to consider how cooperation could be strengthened and programs in biocontrol could be improved.

A number of administrators representing ESCOP and individual agricultural experiment stations also participated in this discussion. A discussion on the five areas of greatest concern follows.

National Coordinating Committee

Organizing a national coordinating committee was considered essential. This area was ranked far above any of the other items of discussion. The committee would establish linkages between the current operating regional committees and improve information exchange and plan national workshops and other activities. Industry representatives should be encouraged to participate in the committee as formal, but non-voting, members. These and other mechanisms should improve coordination and information exchange between the organizations currently involved in biocontrol. Currently, a national committee is concerned with integrated pest management; however, a separate group specifically concerned with biological control research problems is needed. Because of the current research programs on biocontrol at many companies, some consideration should be given as to how the scientists employed by industry can exchange non-proprietary information with other colleagues.

Commonality and Uniqueness

Many of the fundamental concepts for biocontrol are very similar in each of the disciplines. However, some are not. Certain terms presently used in entomology to describe basic concepts either have no equivalents or are interpreted differently in plant pathology, and vice versa. Pathologists, entomologists, and, perhaps, weed scientists could work together to prepare (1) a glossary and (2) review articles and statements on biocontrol. The glossary would define terms common to the disciplines. Review articles and statements would discuss the state of the art and the problem of commonality. However, each discipline has separate and distinct areas that cannot be merged. Efforts should be made to define clearly those areas that are unique for each discipline. Areas that differ conceptually may require distinctly different research approaches.

Curricula and Courses

Land grant universities should consider the possibility of establishing curricula, courses, joint seminars, and other activities specifically designed around the basic concepts of biological control. Several institutions in the United States have developed such curricula and courses, but the total number is small. Established curricula could be changed such that graduate students could specialize in this area. In many institutions, strong interdepartmental programs have been developed in plant protection and integrated pest management. Similar programs should be developed for biological control.

Also, endowed professorships or university chairs in biological control could be established. Industry or private foundations could be contacted for possible funding. Senior scientists who have done outstanding work in biocontrol could be supported by such professorships. One objective of these professorships would be to maintain and strengthen interdisciplinary research and program development. Joint appointments in two or more departments should be considered.

Interdisciplinary Symposia

National and international societies concerned with plant protection should develop and schedule symposia on biological control. These could be held in conjunction with annual meetings or as separately sponsored

events in connection with regional or other meetings. These symposia should be held at periodic intervals to bring together the innovative research leaders to discuss problems limiting advancement of the area and to inform colleagues of current progress in biocontrol. In addition, discussion groups and working groups focused on biocontrol should be scheduled for the international plant protection congresses.

Basic Biological Research

Although specific approaches to achieve this goal were not outlined, additional basic work in biology is needed to provide the knowledge that undergirds biological control research. Biological control cannot be separated as a distinct and separate discipline from the biological sciences. Also, many basic as well as applied biologists should be encouraged to use insects, weeds, or plant pathogens as models for fundamental research.

Other Proposals (not-ranked)

A number of other suggestions were discussed. These are listed below, but they are not ranked.

Establish commodity-oriented interdisciplinary research. Efforts should be made to establish regional and national commodity-oriented research groups involving the various biocontrol disciplines. People directly involved in biocontrol and scientists from other supporting disciplines, such as soil science, should be included.

Examine and revise the committee structure of established regional projects. Scientists from different areas of biocontrol and supporting sciences should be represented wherever possible. This would insure that each committee involves scientists from the range of disciplines necessary to effectively coordinate research. Also members of projects should be participants, not just representatives, and they should be selected on that basis.

Establish common projects at experiment stations. This would encourage experiment stations to establish interdisciplinary task forces or working groups in biocontrol, which would enable individuals not in plant pathology, weed science, or entomology to participate in biocontrol research. Other scientists, whose research is related closely to biological control studies, could be invited to participate.

Identify problems resolvable by biological controls. Major pest control problems should be evaluated as to their potential for being resolved using biological controls. Often research on insect and disease pests focuses on methods other than biological control. Biological controls may not even be part of the research. As a result, opportunities for exploiting biological control systems have been bypassed. To best evaluate the potentials of biological controls, entomologists, plant pathologists, and weed scientists should meet and discuss the ideas and problems. Meetings, such as the conference held in Las Vegas, partly fill this need.

Participate in the International Organization for Biological Control (IOBC). The major participants in IOBC have been, with few exceptions, entomologists. There are opportunities in this organization for greater involvement by representatives from other disciplines. Efforts should be made by the appropriate professional societies within the U.S. to insure full representation of each of the disciplines. The IOBC has an international journal and newsletter. Use of these mechanisms may also enhance cooperation. Opportunities within each aspect of this organization should be examined more fully as one means of improving cooperative relationships.

Provide more time and support for research on biocontrol of weeds. At present, relatively few weed scientists are involved in biocontrol research in the U.S. In fact, many weed scientists think that it is extremely difficult for biocontrol agents to control weeds effectively. Further, the limited number of weed control scientists at many state institutions, with their corresponding time and assignment limitations, mean that they are drawn into research primarily concerned with chemical control. Thus, there is little opportunity to consider control other than chemical. The time commitments and research assignments of weed control scientists should be reassessed at the regional and local level to determine whether or not a greater input could be structured into the area of biocontrol of weeds.

Increase administrative and scientific understanding of biocontrol as a component of integrated pest management. Biocontrol should be a distinct but unique component of integrated pest management. The two terms are not synonymous. However, the effective development of IPM procedures requires a

basic understanding of biocontrol agents and their application. Much of this involves basic biological research as well as its application. Presently, integrated pest management programs have emphasized the importance of expanding the knowledge of biocontrol. To gain that information, biocontrol research must be an integral, but separate, part of IPM. It was suggested that the term "integrated pest management" needs to be changed to "integrated production management." This insures that all the inputs necessary for production are considered. Pest control is just one of many inputs essential for production.

Increase funding for biocontrol. Biocontrol research needs continued and strengthened support. To increase funding, however, funds may need to be reallocated from other research. In view of the long range need for support, the balance of funding must be assessed.

Establish an intersociety award for innovative advances in biocontrol. This should be a major annual award that could be presented either at a joint meeting of two or more professional societies or at a specific annual meeting. The award could be made by a committee composed of representatives of each of the major societies involved in biocontrol, rotated among the various societies, or administered by a "National Biocontrol Coordinating Committee." Funding can be sought either from industry or other agencies. Presentation of the award should be publicized. Hopefully, this would encourage research in biocontrol and provide an opportunity to recognize individuals doing creative and exciting research.

Develop an interdisciplinary newsletter. At present, there is no one central communication mechanism where advances in biocontrol can be disseminated to biocontrol scientists. The IOBC has a quarterly journal where information of this type can be published. However, there is need for timely items to be communicated throughout the biocontrol community in the U.S. This could be in the format of a relatively inexpensive newsletter that could include reports of meetings, new developments, organizational information, and material of interest to research scientists involved in biocontrol.

Support plant health as an "umbrella" discipline. Biocontrol and support for biocontrol needs to be presented as one component under the general objective of maintaining and enhancing plant health. When developing national programs, biological control should not be treated as an isolated discipline, but as an area of science that contributes to the overall enhancement of plant health.

Inventory biocontrol projects. The biocontrol components of the various regional and interregional research projects needs to be identified and characterized. This could also include specific identifiable biocontrol programs at the state level that are fully interdisciplinary. One component of this inventory could be a listing of individuals currently involved in biocontrol projects, along with a statement of their primary research areas.

Use CSRS special grants only for interdisciplinary work. Funding of special grants in biological control should be restricted to proposals that clearly involve research crossing the disciplines of entomology, plant pathology, weed science, virology, or nematology. This hopefully would encourage closer working relationships between scientists in different disciplines.

Establish a new biocontrol journal. A new journal, supported by the four major plant protection societies could improve communication among the scientists and foster interdisciplinary research.

Establish cassette and slide series on biocontrol. Presently, the American Phytopathological Society is considering developing a series of educational cassettes that could be used for teaching, extension programs, or individual scientists to upgrade their background in specific areas outside of their specialization. They plan to ask outstanding individuals to record state-of-the-art presentations on tapes that can be updated and revised periodically. Designing a set of tapes on biocontrol could be one component of this program. This project could involve representatives from various disciplines. The topics would cover interdisciplinary research useful to all the areas in biocontrol. As one adjunct to this program, slide sets illustrating biocontrol concepts and successful approaches to biocontrol could be developed under the aegis of the Biocontrol Coordinating Committee. Sale of these materials could be handled through the professional societies.

LIST OF REGISTRANTS

REGISTRANTS

H. Alford
P.O. 3075
Macero, CO 95618

G. Allen
USDA/CR
Room 6440, South Building
14th & Independence Avenue
Washington, D.C. 20250

M. Altieri
USDA Biological Control of Weeds
1050 San Pablo Avenue
Albany, CA 94706

L. A. Andres
USDA Biological Control of Weed
1050 San Pablo Avenue
Albany, CA 94706

T. G. Andreadis
Department of Entomology
Conn. Agr. Experiment Sta.
P.O. Box 1106
New Haven, CT 06504

J. E. Appleby
Ill. Natural History Survey
607 E. Peabody
Champaign, IL 61820

P. Backman
Department of Botany and
Plant Pathology
Auburn University
Auburn, AL 36849

D. M. Baker
IR-4 Headquarters
McLean Research Lab
Rutgers University Cook College
New Brunswick, NJ 08903

R. Baker
Department of Plant Pathology
Colorado State University
Fort Collins, CO 80523

J. E. Bath
Department of Entomology
Michigan State University
E. Lansing, MI 48824

S. L. Battenfield
Department of Entomology
Michigan State University
E. Lansing, MI 48824

J. W. Beardsley, Jr.
Department of Entomology
University of Hawaii
3050 Maile Way
Honolulu, HI 96822

J. Beavers
2120 Camden Road
Orlando, FL 32803

S. Beer
Cornell University
Department of Plant Pathology
Ithaca, NY 14853

M. Bell
4135 E. Broadway
Phoenix, AZ 85040

W. L. Biehn
IR-4 Headquarters
McLean Research Lab
Rutgers University Cook College
New Brunswick, NJ 08903

D. K. Biever
USDA ARS
Box A
Columbia, MO 65205

L. S. Bird
Department of Plant Sciences
Texas A & M University
College Station, TX 77843

D. J. Boethel
Department of Entomology
Louisiana State University
Baton Rouge, LA 70803

M. G. Boosalis
Department of Plant Pathology
University of Nebraska East Campus
406 Plant Sciences Hall
Lincoln, NE 68583

D. Boucias
Department of Entomology
University of Florida
Gainesville, FL 32611

G. Boush
Department of Entomology
University of Wisconsin-Madison
237 Russell Lab
Madison, WI 53706

D. Boyette
Delta States Res. Center
P.O. Box 285
Stoneville, MS 38776

W. M. Brooks
Department of Entomology
North Carolina University
Raleigh, NC 27650

H. Browning
Texas A & M University
2415 E. Highway 83
Weslaco, TX 78596

J. A. Browning
Plant Sciences Department
Texas A & M University
College Station, TX 77843

W. Bruckart
Plant Disease Research Lab
P.O. Box 1209
Frederick, MD 21701

G. A. Buchanan
Adm. Adv. to S-136
Auburn University
107 Comer Hall
Auburn University, AL 36849

G. W. Buchenau
1215 3rd Street
Brookings, SD 57006

G. Buckingham
P.O. Box 1269
Gainesville, FL 32602

T. Burger
USDA APHIS PPQ
P.O. Box 787
Mission, TX 78572

M. E. Burt
IR-4 Headquarters
McLean Res. Lab
Rutger University Cook College
New Brunswick, NJ 08903

L. E. Caltagirone
1050 San Pablo Avenue
Albany, CA 94706

E. A. Cameron
Department of Entomology
106 Patterson Bldg.
Pennsylvania State University
University Park, PA 16802

J. L. Capinera
Department Zoology and
Entomology
Colorado State University
Fort Collins, CO 80523

R. B. Carlson
82 22nd Ave. N.
Fargo, ND 58102

G. R. Carner
Department of Entomology
Clemson University
Clemson, SC 29631

J. R. Cate
Rt. 3, Box 478
Bryan, TX 77801

R. Charudattan
Department of Plant Pathology
University of Florida
Gainesville, FL 32611

H. C. Chiang
Department of Entomology
University of Minnesota
St. Paul, MN 55108

R. J. Cook
367 Johnson Hall
Washington State University
Pullman, WA 99164

H. Coppel
Department of Entomology
337 Russell Labs
University of Wisconsin
Madison, WI 53706

J. Cota
U.S. Forest Service
180 Canfield Street
Morgantown, WV 26506

T. L. Couch
Abbott Laboratories D-912
14th & Sheridan Road
N. Chicago, IL 60064

J. R. Coulson
Beneficial Insect Intro. Lab
ARS USDA Bldg 417, BARC-East
Beltsville, MD 20705

G. L. Cunningham
USDA APHIS PPQ
P.O. Box 787
Mission, TX 78572

E. A. Curl
Department of Botany, Plant
Pathology and Microbiology
Auburn University
Auburn, AL 36849

D. L. Dahlsten
Div. of Biological Control
University of California
Berkeley, CA 94720

J. M. Davidson
1022 McCarty Hall
University of Florida
Gainesville, FL 32611

D. W. Davis
Department of Biology UMC 53
Utah State University
Logan, UT 84322

J. R. Davis
University of Idaho Research
and Extension Center
University of Idaho
Aberdeen, ID 83210

C. W. Donoho, Jr.
Administration Building
Ohio Agri. Res. and Dev. Center
Wooster, OH 44691

K. Dorschner
2612 Lakevale Drive
Vienna, VA 22180

N. Dubois
Center for Biological Control
of NE Forest Insects and Diseases
51 Mill Pond Road
Hamden, CT 06514

H. T. Dulmage
8 Edgewater Dl.
Brownsville, TX 78521

P. Dunn
American Embassy Agriculture
APO, NY 09794

P. E. Dunn
Department of Entomology
Purdue University
W. Lafayette, IN 47909

G. D. Easton
IAREC Box 30
Prosser, WA 99350

L. E. Ehler
Department of Entomology
University of California
Davis, CA 95616

R. S. Eikenbary
Department of Entomology
Oklahoma State University
Stillwater, OK 74078

J. J. Ellington
P.O. Box 3BE
Department of Entomology and
Plant Pathology
New Mexico State University
Las Cruces, NM 88003

J. E. Elson
IR-4 Headquarters
McLean Res. Lab
Rutgers University Cook College
New Brunswick, NJ 80903

L. K. Etzel
8630 Arbor Drive
El Cerrito, CA 94530

H. Fairchild
USDA APHIS PPQ
P.O. Box 787
Mission, TX 78572

L. A. Falcon
Department Entomology-
Pathology
333 Hilgard Hall
University of California
Berkeley, CA 94720

B. A. Federici
Div. of Biological Control
University of California
Riverside, CA 92521

M. P. Ferguson
IR-4 Program
116B Street
Davis, CA 95616

R. S. Ferriss
Department of Plant Pathology
S-305 Agr. Science North
University of Kentucky
Lexington, KT 40546

D. Ferro
Department of Entomology
University of Massachusetts
Amherst, MA 01003

T. Fincher
USDA ARS VTEL
P.O. Drawer GE
College Station, TX 77841

J. R. Finney
Department of Biology
Memorial University
St. John's Newfoundland
Canada A1C 5S7

T. W. Fisher
Div. of Biological Control
University of California
Riverside, CA 92521

R. Flanders
Department of Entomology
Purdue University
W. Lafayette, IN 47907

R. E. Frisbie
311 Systems Bldg.
Texas A & M University
College Station, TX 77843

J. R. Fuxa
Department of Entomology
Louisiana State University
Baton Rouge, LA 70803

R. E. Fye
USDA ARS
3706 West Nob Hill Blvd.
Yakima, WA 98902

W. A. Gardner
Department of Entomology
Georgia Experiment Station
Griffin, GA 30212

R. Georgis
Nematode Farm, Inc.
2617 San Pablo Avenue
Berkeley, CA 94702

D. Gonzalez
Div. of Biological Control
University of California
Riverside, CA 92521

G. Gordh
Div. of Biological Control
University of California
Riverside, CA 92521

A. Gotlieb
University of Vermont
and State Agr. College
Burlington, VT 05405

R. R. Granados
Boyce Thompson Institute
Cornell University Tower Roa
Ithaca, NY 14853

C. Grau
Department of Plant Patholo
University of Wisconsin
Madison, WI 53706

P. Grau
Abbott Laboratories
1520 E. Shaw #107
Fresno, CA 93710

G. D. Griffin
USDA-ARS, UMC-63
Utah State University
Logan, UT 84322

C. A. Griffith
Noble Foundation
Route One
Ardmore, OK 73401

R. T. Guest
IR-4 Headquarters
McLean Res. Lab
Rutgers University Cook College
New Brunswick, NJ 08903

K. S. Hagen
Department of Biological Control
1050 San Pablo Avenue
University of California
Albany, CA 94706

M. Halsey
Department of Botany and Plant Pathology
Oregon State University
Corvallis, OR 97331

J. J. Hamm
USDA ARS
Georgia Coastal Plain Exp. Sta.
Tifton, GA 31793

J. Hancock
Department of Plant Pathology
147 Hilgard Hall
University of California
Berkeley, CA 94720

C. Hansen
Rohm & Haas Co.
Independent Mall West
Philadelphia, PA 19105

J. D. Harper
Department of Zoology-Entomology
Auburn University
Auburn, AL 36849

D. L. Haynes
Department of Entomology
Michigan State University
E. Lansing, MI 48824

E. Hazard
Gulf Coast Mosquito Res. Lab.
USDA ARS
Avenue J. Chennault
Lake Charles, LA 70601

J. E. Henry
USDA ARS Rangeland Insect Lab
Montana State University
Bozeman, MT 59717

L. J. Herr
Department of Plant Pathology
OSU OARDC
Wooster, OH 44691

D. C. Herzog
Agri. Res. and Ed. Center
Rt. 3, Box 638
Quincy, FL 32531

R. B. Hine
1101 Camino De Los Padres
Tucson, AZ 85718

H. C. Hoch
Department of Plant Pathology
NY State Agri. Exper. Sta.
Geneva, NY 14456

G. E. Holcomb
Department of Plant Pathology and Crop Physiology
Louisiana State University
Baton Rouge, LA 70803

T. O. Holtzer
Department of Entomology
University of Nebraska
Plant Industry Bldg.
Lincoln, NE 68583-0816

G. Hooper
Department of Plant Pathology and Physiology
Virginia Polytechnic Inst. and State University
Blacksburg, VA 24061

M. Houseweart
227 Nutting Hall
University of Maine
Orondo, ME 04469

M. A. Hoy
Department of Entomology
201 Wellman Hall
University of California
Berkeley, CA 94720

S. C. Hoyt
Tree Fruit Res. Center
1100 N. Western
Wenatchee, WA 98801

D. M. Huber
Botany and Plant Pathology
Purdue University
W. Lafayette, IN 47907

E. Huddleston
P.O. Box 3BE
New Mexico State University
Las Cruces, NM 88003

C. B. Huffaker
3540 Springhill Road
Lafayette, CA 94549

C. Ignoffo
2905 W. Rollins, Apt. B6
Columbia, MO 65201

A. W. Ip
Corning Glass Works
SP CVI-10A
Corning, NY 14831

N. I. James
219 Agri. Sciences Bldg.
Washington State University
Pullman, WA 99164

L. F. Johnson
Department of Entomology and Plant Pathology
University of Tennessee
Knoxville, TN 37901

R. L. Jones
Department of Entomology
University of Minnesota
1980 Folwell Avenue
St. Paul, MN 55108

W. A. Jones
USDA ARS
P.O. Box 225
Stoneville, MS 38776

C. Kado
Department of Plant Pathology
University of California
Davis, CA 95616

H. K. Kaya
Div. of Nematology
University of California
Davis, CA 95616

C. B. Keil
Department of Entomology
University of California
Riverside, CA 92521

A. Kelman
1630 Linden Drive
Department of Plant Pathology
University of Wisconsin-Madison
Madison, WI 53706

C. M. Kenerley
Department Plant Pathology
North Carolina St. University
Raleigh, NC 27650

D. S. Kenney
Abbott Lab Research Center
36 Oakwood Road
Long Grove, IL 60047

E. E. King
USDA ARS Delta States Area
Stoneville,MS 38776

J. O. Kirkpatrick
BR Supply Company
P.O. Box 845
Exeter, CA 93221

L. P. Kish
Department of Plant, Soil and Entomology
University of Idaho
Aberdeen, ID 83210

M. Knittel
U.S. Environmental Protection
Agency
200 SW 35th
Corvallis, OR 97333

L. T. Kok
Department of Entomology
Price Hall
Virginia Polytechic Inst.
and State University
Blacksburg, VA 24061

T. Kommedahl
Stakman Hall of Plant Pathology
1519 Gortner Avenue
University of Minnesota
St. Paul, MN 55108

R. H. Kupelian
IR-4 Headquaters
McLean Res. Lab
Rutgers University Cook College
New Brunswick, NJ 08903

R. Lavigne
Plant Sciences Div.
P.O. Box 3354 University Station
University of Wyoming
Laramie, WY 82071

F. B. Lewis
Center for Biological Control NE
Forest Insects and Diseases
51 Mill Pond Road
Hamden, CT 06514

W. J. Lewis
USDA-ARS
Southern Grain Insect Rec. Lab.
Tifton, GA 31793

L. Li
Guang Dong Entomological
Institute
Guang Zhou
Peoples Republic of China

B. Lighthart
U.S. Env. Protection Agency
200 SW 35th
Corvalis, OR 97333

J. E. Lindegren
2826 E. Los Altos
Fresno, CA 93710

S. Lindow
Department of Plant Pathology
University of California
Berkeley, CA 94720

L. J. Liu
University of Puerto Rico
Mayaguez, Puerto Rico 00708

J. Lockwood
Department of Botany
and Plant Pathology
Michigan State University
E. Lansing, MI 48824

P. L. Love
CSRS USDA, Rm. 6440-S
14th & Independence SW
Washington, DC 20250

R. F. Luck
Div. of Biological Control
University of California
Riverside, CA 92521

R. G. Luttrell
Drawer EM
Bulldog Circle Nr. 34
Mississippi State, MS 39762

W. L. MacDonald
Department of Plant Pathology
and Agricultural Microbiology
West Virginia University
401 Brooks Hall
P.O. Box 6057
Morgantown, WV 26506-6057

D. R. MacKenzie
Department of Plant Pathology
and Crop Physiology
302 Life Sciences Building
Louisiana State University
Baton Rouge, LA 70803

J. V. Maddox
Illinois Natural Hist. Survey
607 East Peabody
Champaign, IL 61820

R. Mankau
Department of Nematology
University of California
Riverside, CA 92521

W. J. Manning
Department of Plant Pathology
Fernald Hall
University of Massachusetts
Amherst, MA 01003

G. M. Markle
IR-4 Headquarters
McLean Research Lab
Rutgers University Cook College
New Brunswick, NJ 08903

C. A. Martinson
425 Bessey Hall
Iowa State University
Ames, IA 50010

F. Matsumura
Pesticide Research Center
Michigan State University
E. Lansing, MI 48824-1311

F. Maxwell
Department of Entomology
Texas A & M University
College Station, TX 78340

J. McCaffrey
Department of Plant Soil and
Entomological Sciences
University of Idaho
Moscow, ID 83843

W. J. McCarthy
Pesticide Research Lab
Penn. State University
University Park, PA 16802

C. W. McCoy
University of Florida
Box 1088
A. R. E. C.
Lake Alfred, FL 33850

B. L. McFarland
Research Microbiologist
Chevron Chem. Biotech. Group
940 Hensley Street
Richmond, CA 94804

C. W. Meister
Pesticide Research Lab
IFAS
University of Florida
Gainesvlle, FL 32611

J. A. Menge
Department of Plant Pathology
University of California Riverside
Riverside, CA 92521

J. W. Mertins
Department of Entomology
Iowa State University
Ames, IA 50011

D. E. Meyerdirk
Boyden Fruit and Vegetable
Insects Research Lab
USDA ARS
University of California
Riverside, CA 92521

E. Milewski
Nat'l Inst. of Health
Bldg. 31, Room 3B10
Bethesda, MD 20205

I. J. Misaghi
Department of Plant Pathology
University of Arizona
Tucson, AZ 85721

L. W. Moore
3420 SW Orchard St.
Corvallis, OR 97330

M. Mount
Department of Plant Pathology
Fernald Hall
University of Massachusetts
Amherst, MA 01003

E. Mulrean
123 W. Granada
Phoenix, AZ 85003

L. Nanxin
Guang Dong Entomological
Institute
Guang Zhou
Peoples Republic of China

M. R. Nelson
Department of Plant Pathology
University of Arizona
Tucson, AZ 85721

Z. Noon
Nematode Farm, Inc.
2617 San Pablo Avenue
Berkeley, CA 94702

G. L. Nordin
Department of Entomology
University of Kentucky
Lexington, KY 40546

J. F. Norland
The Upjohn Company
7171 Portage Road
Kalamazoo, MI 49001

R. Oetting
Department of Entomology
Georgia Experiment Station
University of Georgia
Experiment, GA 30212

W. Olkowski
1307 Acton St.
Berkeley, CA 94706

C. Y. Oseto
Department of Entomology
North Dakota State University
Fargo, ND 58105

J. Owens
P.O. Box 3BE
New Mexico State University
Las Cruces, NM 88003

C. A. Panton
P.O. Box 20891
Greensboro, NC 27420

G. C. Papavizas
11300 Cedar Lane
Beltsville, MD 20705

P. H. Parham
Plant Health Res. and Dev.
The Upjohn Company
Kalamazoo, MI 49001

P. Parker
USDA APHIS PPQ
P.O. Box 787
Mission, TX 78572

R. Parrella
Department of Entomology
University of California
Riverside, CA 92521

J. Paxton
Department of Plant Pathology
University of Illinois
N 519 Turner Hall
1102 S Goodwin Avenue
Urbana, IL 61801

H. N. Pitre
Department of Entomology
Drawer EM
Mississippi State University
Mississippi State, MS 39762

F. Poston
Department of Entomology
Kansas State University
Manhattan, KS 66506

J. Powell
USDA ARS P.O. Box 225
Stoneville, MS 38776

A. R. Putnam
Department of Botany
and Plant Pathology
105 Pesticide Research Center
Michigan State University
E. Lansing, MI 48824

P. C. Quimby, Jr.
Southern Weed Science Lab
USDA ARS
P.O. Box 225
Stoneville, MS 38776

R. J. Quinlan
Tate & Lyle Ltd.
P.O. Box 68
Reading RG6 2BX
Berkshire, England

W. A. Ramoska
Department of Entomology
Kansas State University
Manhattan, KS 66506

C. D. Ranney
USDA ARS
P.O. Box 225
Stoneville, MS 38776

C. Reichelderfer
Department of Entomology
University of Maryland
College Park, MD 20782

W. H. Ridings
Department of Plant Pathology
and Physiology
Clemson University
Clemson, SC 29631

D. W. Roberts
Insect Pathology Resource Ctr.
Boyce-Thompson Institute
Tower Road
Cornell University
Ithaca, NY 14853

R. Rodriguez-Kabana
267 Funchess Hall
Auburn University
Auburn, AL 36830

R. J. Sauer
Agric. Experiment Station
1420 Eckles Avenue
220 Coffey Hall
University of Minnesota
St. Paul, MN 55108

N. Schaad
Department of Plant, Soil
and Entomological Sciences
University of Idaho
Moscow, ID 83843

A. Schmitthenner
Department of Plant Pathology
Ohio Agri. Res. and Dev. Center
Wooster, OH 44691

J. Schwer
Eli Lilly & Co.
P.O. Box 708
Greenfield, IN 46140

J. Sentz
International Program
College of Agriculture
1420 Eckles Avenue
277 Coffey Hall
University of Minnesota
St. Paul, MN 55108

M. Shapiro
35 S Sandwich Road
Mashpee, MA 02649

T. R. Shieh
Sandoz Inc.
5th & G Streets
Wasco, CA 93280

R. J. Smith, Jr.
USDA ARS
P.O. Box 287
Stuttgart, AR 72160

B. Sneh
Department of Botany
and Plant Pathology
Colorado State University
Fort Collins, CO 80523

N. R. Spencer
USDA ARS SWSL
P.O. Box 225
Stoneville, MS 38776

S. Spencer
Plant Industry Div.
NC Department of Agriculture
P.O. Box 27647
Raleight, NC 27611

H. W. Spurr, Jr.
Oxford Tobacco Laboratory
Rt. 2, Box 16G
Oxford, NC 27565

R. W. Stack
Department of Plant Pathology
North Dakota State University
Fargo, ND 58105

C. D. Steelman
Louisiana Agri. Exp. Station
P.O. Drawer E. University Station
Louisiana State University
Baton Rouge, LA 70893

F. W. Stehr
Department of Entomology
Michigan State University
E. Lansing, MI 48824

M. W. Stimmann
2402 Elenoil Lane
Davis, CA 95616

D. Streett
Rangeland Insect Lab
Montana State University
Bozeman, MT 59717

M. D. Summers
Department of Entomology
Texas A & M
College Station, TX 77843

M. J. Tauber
Department of Entomology
Cornell University
Ithaca, NY 14853

D. TeBeest
Department of Plant Pathology
University of Arkansas
Fayetteville, AR 72701

G. E. Templeton
Department of Plant Pathology
University of Arkansas
Fayetteville, AR 72701

R. L. Thompson
Agri. Experiment Station
University of Minnesota
1420 Eckles Avenue
St. Paul, MN 55108

S. A. Tolin
Department of Plant Pathology
and Physiology
Virginia Polytechnic Inst.
and State University
Blacksburg, VA 24061

P. H. Tsao
Department of Plant Pathology
University of California
Riverside, CA 92521

E. Ummel
Sandoz, Inc.
480 Camino Del Rio South
San Diego, CA 92108

C. G. Van Dyke
Department of Botany
North Carolina State University
Raleigh, NC 27650

L. O. Warren
Agricultural Experiment Station
217 Agriculture Building
University of Arkansas
Fayetteville, AR 72701

T. F. Watson
Department of Entomology
University of Arizona
Tucson, AZ 85721

L. G. Weathers
College of Natural and
Agricultural Sciences
University of California
Riverside, CA 92521

G. J. Weidemann
Department of Plant Pathology
217 Plant Sciences
University of Arkansas
Fayetteville, AR 72701

A. R. Weinhold
Department of Plant Pathology
University of California
Berkeley, CA 94720

R. M. Weseloh
Department of Entomology
Connecticut Agricultural
Experiment Station
New Haven, CT 06504

P. H. Westigard
Oreson Exp. Station
569 Hanley Road
Medford, OR 97502

R. Wharton
1111 Dexter Drive
College Station, TX 77840

W. H. Whitcomb
Department of Entomology
and Nematology
3103 McCarty Hall
University of Florida
Gainesville, FL 32611

J. C. White
Chevron Chemical Co.
P.O. Box 3744
San Francisco, CA 94119

M. Miller Wideman
Monsanto
800 N Lindbergh
St. Louis, MO 63166

H. Wilkinson
Department of Plant Pathology
University of Illinois
Turner Hall
702 S Goodwin Avenue
Urbana, IL 61801

J. D. Wilkinson
USDA ARS, Box A
Biological Control of Insects Lab
Columbia, MO 65201

R. N. Williams
Department of Entomology
OARDC
Wooster, OH 44691

A. Wilson
Nematode Farm, Inc.
2617 San Pablo Avenue
Berkeley, CA 94702

K. G. Wilson
Plant Industry Div.
NC Department of Agriculture
P.O. Box 27647
Raleigh, NC 27611

H. A. Wood
Boyce Thompson Institute
Tower Road
Ithaca, NY 14853

A. D. Worsham
4005 Picardy Drive
Raleigh, NC 27612

Bruno Wuerzer
BASF AG
D-APE/FH, Postfach 220
6703 Limburger Hof
GERMANY

W. G. Yendol
Pesticide Research Lab
Pennsylvania State University
University Park, PA 16802

S. Young
Department of Entomology
University of Arkansas
Fayetteville, AR 72701

N. N. Youssef
Department of Biology
Utah State University
Logan, UT 84322

APPENDICES

APPENDIX A-1

BIOTYPES

Ideas to Improve the Use of Naturally Occurring Biotypes

1. Identify important traits to be selected.
2. Detect, identify and quantify biological and ecological differences among biotypes.
3. Select biotypes from disease-suppressive soils.
4. Identify factors that induce naturally occurring biotypes (in arthropods).
5. Select biotypes that colonize the rhizosphere.
6. Identify crop cultivars that excel in selecting desirable biological control biotypes.
7. Conserve or preserve natually occurring biotypes.
8. Study the population biology of naturally occurring biotypes.
9. Increase foreign exploration for biotypes of microbials.
10. Identify biotypes that are effective against plant pathogens, insects, and weeds (inclusive) (i.e., increase host range of biotypes).
11. Understand relationships between cropping and cultural practices on the balance of soil-borne pathotypes.
12. Identify geographical range and extent of occurrence of identified biotypes.
13. Model host-biotype-environment interactions.
14. Study the role of plant exudates in selection and/or (potatoes) shift in the balance of biotypes (plant pathogens and non-pathogens).
15. Objectively identify biotypes (perhaps chemical laboratory tests).
16. Define biotype habitat-specificity.
17. Evaluate variation in and population genetic consequences of parasitoid mating strategies.
18. Identify organismic products or processes critical to biological control.
19. Conduct population genetic studies to analyze previously established parasitoid populations.
20. Define host range/specificity of microbial pathotypes.

APPENDIX A-2

BIOTYPES

Ideas to Genetically Improve Biotypes Through Standard Breeding Practices, Including Mutagenesis

1. Develop new biotypes with enhanced biological control abilities.
2. Develop and/or improve tolerance to pesticides in biological control agents in plant pathology.
3. Develop sensitive bioassay protocols for selecting microbial pathogens.
4. Identify useful/important traits to be selected.
5. Produce or identify visible genetic markers.
6. Manage biotypes through managing genotypes of the host plants.
7. Develop heterosis in biotypes of imported natural enemies of pest arthropods.
8. Improve mass-culture techniques to allow selection of biotypes to occur.
9. Determine the genetic basis of host selection behavior in parasites and predators.
10. Document field efficacy of improved strains of arthropod biocontrol agents.
11. Develop high thru-put *in vitro* screening for mutant mycoherbicides (insecticides).
12. Develop techniques to produce protoplasts to use in a breeding program of fungi used in biological control.
13. Develop methods for enhancing reproductive isolation of genetically improved strains.
14. Develop release strategies for injecting major genes into natural populations (replace populations, mix biotypes).
15. Compare competitiveness of artificially derived biotypes with naturally occurring biotypes.
16. Increase the ability to develop the sexual stage of fungal antagonists, as population genetics cannot be done without the sexual stage.
17. Select multiple variable biotypes, i.e. combine insecticide resistance plus temperature tolerance.
18. Develop biotypes in the laboratory under diverse environmental conditions.
19. For asexual fungal antagonists, develop screening procedures to select parasexual intermediates.
20. Develop theoretical population genetics concerning selection before release of exotic species.

APPENDIX A-3

BIOTYPES

Ideas to Avoid/Prevent Deterioration of Biotypes

1. Develop a rapid bioassay to detect biotype deterioration.
2. Standardize quality control monitoring techniques (both lab and field aspects) for producing biological control agents.
3. Develop strategies for maintaining desirable phenotypic characteristics.
4. Identify environmental limits and survival and function of biotypes of pathogen antagonists.
5. Develop ways to maintain genetic variability in thelytokous strains of imported parasites of arthropod pests.
6. Develop strategies for maintaining genetic integrity of biotypes of arthropod natural enemies (in mass rearing of parasites).
7. Establish large, long term repositories of bioytpes of microorganisms (organisms are often lost when scientists retire).
8. Improve understanding of sex-ratio determination in parasitic Hymenoptera.

APPENDIX A-4

BIOTYPES

Research Ideas, From a Molecular Approach, to Enhance or Improve the Use of Biotypes in Biological Control

1. Examine stability of recombinant organisms in the environment.
2. Determine mechanisms of instability.
3. Examine the evolution of biotypes in an agricultural environment.
4. Examine the genetic response of the host to bioengineered organisms.
5. Conduct research to enhance environmental stability.
6. Establish specific genetic and serological markers for identifying biocontrol agents.
7. Develop methods for selecting biotypes *in vivo*.
8. Isolate gene probes for diagnosis.
9. Identify existing biotypes (*in vivo*).
10. Develop culture collections and/or an information network of engineered agents indexed by desirable traits.
11. Develop protocols for safety testing/registration of genetically engineered organisms.
12. Examine the effects of induced changes in organisms on the ecosystem (including other microbial agents).
13. Determine whether introduced genes might be transferred to other organisms.
14. Examine the ramifications of "survival windows," or controlled longevity, of the engineered organism.
15. Genetically manipulate organisms to improve their ability to be cultured.
16. Define available biocontrol mechanisms.
17. Identify and develop gene pools of desirable characteristics.
18. Maintain familiarity with developing recombinant DNA technology for potentially useful applications.
19. Educate the consumer regarding recombinant DNA-bioengineered agents.
20. Identify genetic regions in eukaryotes responsible for pathogenic processes.
21. Identify gene products useful for biological control and clone the genes into expression vectors.
22. Develop methods for *in vitro* cell culture production of gene products useful for biological control.
23. Examine changes in the isolated agent induced by culturing or isolation conditions.
24. Modify organisms to improve characteristics that enable successful application in the field.
25. Develop strategies to exploit multiple biotypes.

APPENDIX A-5

BIOTYPES

Some Successes of Naturally Occurring or Genetically Improved Biotypes

Entomology

1. The Persian biotype of *Trioxys pallidus* is more effective than the French biotype in controlling the walnut aphid in California.
2. *Bacillus thuringiensis* was thought to be specific to Lepidoptera, but recently (1977) a biotype (*Israelensis*) very active against mosquito and blackfly larvae was found and now is commercially available.
3. The parasitoid, *Comperiella bifasciata*, has biotypes effective against red scale and yellow scale.
4. *Steinernema feltiae* (also known as *Neoaplectana carpocapsae*), the "Breton strain," is more effective than the DD-136 strain.
5. Predatory mites (*Metaseiulus occidentalis* Phytoseiidae) have been selected for pesticide resistances (carbaryl and permethrin) in the laboratory and are effective in the field.
6. Various biotypes of *Verticillium lecanii* are commercially available to control different insect species. For example, one biotype controls aphids, another controls whiteflies.

Plant Pathology

1. A biotype of *Trichoderma viride*, particularly T-1-R9, which is resistant to benomyl, is more effective in controlling *Fusarium* wilt of chrysanthemum than wild type T-1. The improved biotype was developed by irradiation.
2. *Agrobacterium tumefaciens* (K-84 strain) suppresses virulent strains of *A. tumefaciens* that cause crown gall.
3. "Take-all" disease of wheat is controlled by seed coating with biotypes of *Pseudomonas putida* bacteria.
4. *Colletotrichum gloeosporioides* f. sp. *aeschynomene* is used commercially for controlling northern joint vetch, a weed in rice. A biotype, *C. gloeosporioides* f. sp. *jussiaea*, controls wing water primrose.
5. *Trichoderma* biotype has suppressed *Fusarium* wilt in greenhouse carnations.
6. Biotypes of mycorrhizal fungi, *Glomus mosseae*, improve the nutrition of plants over other strains.
7. Chestnut blight is controlled by hypovirulent biotypes of *Endothia parasitica*.
8. Soybean rhizosphere bacteria strains can significantly increase soybean yields by reducing *Phytophthora* root rot.
9. *Trichoderma* strains vary in their effectiveness; some are effective against *Pythium* and others against *Rhizoctonia*.

APPENDIX B

DATA MANAGEMENT

Barriers to the Betterment of Biological Control Data Collection, Management, and Exchange

1. Universally acceptable systems.
2. Lack of effective communication between scientists and agencies (governmental and university).
3. Lack of general awareness of what data bases, literature, and information files are available.
4. Lack of an overall organization.
5. Acceptance of a central depository of information.
6. Lack of standardized formats in data collection techniques and management.
7. Reluctance of scientists to contribute current research data.
8. Taxonomy (precise identification) of biocontrol agents.
9. Inconsistency in reporting ratings (evaluations of intensity).
10. Patent rights and royalties.
11. Governmental (federal and state) regulations recording environmental parameters.
12. Inadequate sampling methods.
13. Compatibility and interchangeability of software and hardware.
14. Inability to interpret data.
15. Competition between institutions.
16. Unfamiliarity of scientists with current development in computer technology and facilities.
17. Personnel trained and willing to participate in the system.
18. Planning difficulties in finance and technology.
19. Privileged information regarding publishing rights.
20. Inadequate funding.
21. Lack of communication between disciplines.
22. Microbial specificity.
23. Lack of database compilation of available information.
24. Lack of cross-referencing.
25. Climatic effects on microbial agents.
26. Availability of equipment.
27. Cost of data collection equipment.
28. Understanding of the use of applied technology in biocontrol agents.
29. Lack of interpretative computer models.
30. Simplified format.
31. Competition between disciplines.
32. Not fully aware of available literature retrieval systems.
33. Source of agents use products.

APPENDIX C-1

SAMPLING

Weak Links in Sampling Technology Relative to Biological Control

1. Detecting, quantifying, and evaluating low population densities.
2. Patterns of horizontal and vertical dispersion and distribution.
3. Estimating age-specific natural enemy mortality.
4. Predator, prey, plant phenology, and synchrony relationships.
5. Fast, reliable counting.
6. Developing sampling methods for growers and PCA's for decision-making.
7. Sample size vs. cost.
8. Data handling and analysis.
9. Initial isolation media.
10. Rapid identification of strains and races.
11. Population density vs. biocontrol.
12. Permanency of host and mobility of pest.

APPENDIX C-2

SAMPLING

Research Ideas to Produce the Maximum Return in Increasing the Effective Use of a Biocontrol Agent

1. Rapid identification of biocontrol agent (i.e., pathogens, biotypes, strain relationships).
2. All-encompassing interdisciplinary and multipurpose sampling systems for commercial and non-commercial use, includes design as a management variable, finding optimal habitats, and developing model systems for interdisciplinary sampling.
3. Measure effectiveness of biocontrol agents, includes identifying potential targets and non-targets and measuring control.
4. Develop simple, practical sampling methods for growers and researchers.
5. Develop new selective media, including specific techniques for detecting and quantifying agents.
6. Low density sampling over space and time—migratory species (including low density habitats).
7. Spatial distribution at subsites, including identification of rhizosphere vs. rhizoplane.
8. Recognize and measure the expression of disease biocontrol.
9. Develop pheromones for detection.
10. Sampling based on parasite behavior-agent based system.
11. Sample for quality of inoculum, includes measuring *in situ* activity.
12. Develop collection (data) systems for precise lay inputs.
13. Monitor abiotic vs. biotic environment.
14. Sample single-parasite, multi-pest system; multi-habitat sytems; and multi-parasite, single pest systems.
15. Develop educational, computer-based, sampling systems.
16. Treat habitats to increase biocontrol populations for more efficient sampling.
17. Automate sampling techniques.
18. Measure development rates.
19. Sampling techniques for host gardens (trap plantings).
20. Integrate spatial/temporal dimensions in algorithm, includes selecting sampling sites.
21. Remote sensing.
22. New marking technology.
23. Sampling institutional constraints.
24. Total insect recovery: increase efficiency.

APPENDIX D

POPULATION DYNAMICS/MODELING

Research Needs Ranked from Highest to Lowest Priority

1. Improved techniques for identification, quantification, isolation, sampling, and impact studies.
2. Identifying key mortality factors of the target organism.
3. Models of the phenological relationships between hosts, pests, and biocontrol agents.
4. Studies incorporating microenvironmental effects on population dynamics.
5. Determination of key factors affecting biocontrol interactions.
6. Population dynamics of the target organism at low or endemic levels.
7. Behavioral interactions between organism and host.
8. Population genetics aspects of biological control.
9. Long term studies on population changes.
10. Characterizing environmental factors that influence population changes.
11. The relationship between host population structure and stability of biocontrol agents.
12. Short, temporal range predictive models.
13. Constraints on population dynamics imposed by ecological energetic effects.
14. Mechanisms of biocontrol effects.
15. Techniques to build populations of biocontrol agents in lab or field.
16. Factors limiting the application of individual models over large geographic areas.
17. Survival of microbial biocontrol agents.
18. Conceptual framework to deal with population changes.
19. Studies of sparse populations.
20. Population quality aspects.
21. Effects of site differences on population dynamics.
22. Areas of modeling that advance biocontrol; community aspects into biocontrol modeling.
23. Integrated population and community aspects into biocontrol modeling.
24. Studies on the interactions between multiple biocontrol agents.
25. Genetic modification to improve biocontrol effectiveness.
26. Seasonal dynamics of the pest in absence of the biocontrol agent.
27. Variation in plant quality as it affects population dynamics.
28. Minimum host density for biocontrol agent survival.
29. Frequency of biological control agents in the population.
30. Interspecific competition between predators and parasitoids.
31. Positive and negative effects of management practices on biocontrol interaction.
32. Effects on biocontrol of short and long range spatial movements.
33. Effects of pest population age structure on susceptibility to the biocontrol agent.
34. Measuring competitive effects.
35. Lack of models representing pests in different areas.
36. The need for interdisciplinary terminology and reporting methods.
37. Relate biocontrol to the ecology of the area; especially, non-managed plants.
38. Improved ways to measure life history parameters.
39. Interactions between qualitative and quantitative features of populations.
40. Insectivorus bird impacts.
41. The relationship between activity levels and population levels.
42. For those pests which exploit a sequence of hosts, what are the successive changes in biocontrol interactions?
43. Impact of spiders as biocontrol agents.
44. Comparative analysis of climatic release, induced and exotic.

45. Host race formation with reference to biocontrol of weeds.
46. Quantification of plant population dynamics as affected by phytophagous insect and pathogen populations.
47. Population dynamic relationships of biocontrol agents and non-target organisms.
48. Modification of host populations to enhance biocontrol effectiveness.
49. Capacity of parasites to damage the host crop.
50. Gene flow in interacting host-parasite interactions.
51. Reproductive abilities of biocontrol agents.
52. Plant stress effects on the biocontrol interaction.
53. Virulence versus fitness in population dynamics.
54. Negative impacts of biocontrol agents.
55. Improved detection and qualification methods for all biocontrol components.
56. Plant competition and succession under the impact of weed biocontrol programs.
57. Pest and biocontrol agent model development.
58. Microclimatology.
59. Macroclimatology.
60. Studies on vectors of weed control pathogens.
61. Reproductive characteristics of weeds.
62. Measuring changes in adaptability.
63. Taxonomic definitions.
64. Explore the gene-for-gene concept for biocontrol agents and hosts.
65. Develop attack models.
66. Spatial distribution of pathogens.
67. Population behavior versus individual behavior.
68. Population phenology.

APPENDIX E

INTEGRATED PEST MANAGEMENT AND BIOLOGICAL CONTROL

Researchable Issues (not priortized)

1. Interactions among organisms in the system.
2. Knowledge and methods of evaluating the impact of biocontrol agents on a pest population over short and long term.
3. Detection and sampling methods for biocontrol agents and targets at various densities.
4. Accurate identification of organisms in the IPM system.
5. Predictive (short-term) capabilities for changes in biocontrol agent/pest densities.
6. Educate user.
7. Develop and maintain reliable sources of agents—availability, quality.
8. Effects of agents below economic injury level.
9. Interaction of agent and cultural practices (farming methods).
10. Interaction of pesticide and agent, including differential kill rates.
11. Model effects of abiotic factors on agents and agent interactions over time and space.
12. Recognition of risk avoidance perception on yield variability.
13. Identification of germplasm complementary to biocontrol and IPM.
14. Agent behavior (broad sense) in monoculture.
15. Relation of non-agricultural areas to agent, including weeds as refuge.
16. Methods of field evaluation of agents.
17. Identification of economically feasible agents.
18. Information on dispersal and distribution of agents (natural and commercial).
19. Better formulation and application technology (microbials and others).
20. Evaluation of inundative releases.
21. Biotic and abiotic factors affecting agent effectiveness, including system manipulation.
22. Pre-research evaluation of a biocontrol program in IPM, including identification of pest or pest complex that causes identifiable damage or disease.
23. Economics of use of biocontrol.
24. Identification and research of gaps in the basic biology of pests, biocontrols, and pest-crop systems.
25. Compatibility of biological control with agronomic practices and microbial and chemical pesticides.
26. Regulation of pesticides for biocontrol goals.
27. Effects of distribution on efficiency of sampling and statistical analysis.
28. Ecological basis for distribution patterns.
29. Root exudate management for enhancement of biological agents (impact of predisposition of host plant).
30. Predator-parasite-pathogen/prey relations.
31. Establish tolerance levels for pest species.
32. Impact of conservation tillage and host plant resistance on antagonists, pathogens, insects, weeds, and nematodes.
33. Impact of plant stress on interaction between bioagents and pests.
34. Role of biocontrol agents in "resistance" management.
35. Prediction of pest populations considering impact of biocontrol agent—success or failure prediction.
36. Economic value of biocontrol in total production system.
37. Education of pesticide users to biocontrol value.
38. Development of farm equipment that advances biocontrol.
39. "Additivity" of mortality due to multiple biocontrol agents.

40. Behavior biology outside the crop management economic unit.
41. Information on overwintering sites.
42. Effect of management practices to enhance biocontrol; development of varieties that enhance biocontrol interplanting.
43. Development of soil ecology data for soil management-soil pesticide impact; investigation of soil microarthropods as biocontrol agents.
44. Ecosystem analysis to identify characteristics of needed biocontrol agents.
45. Institutional constraints on biocontrol in IPM; risks and incentives in programs, social goals, multiple producers.
46. Impact of "payment-in-kind" (PIK) programs on IPM and biocontrol—plantings for enhanced biochemical goals.
47. Establish what predator (parasite)/prey ratios are effective in controlling the pest.
48. Compatibility of biological control with other control strategies.
49. Develop host genotypes that support or enhance biological control agents.
50. Determine natural enemy-host-crop phenological relationships.
51. Mammalian safety of biological control agents.
52. Effect of biological agents on non-target plant and animal life.
53. Search for additional biological control agents of weeds.
54. Compatibility among biological control agents.
55. Identify biological control agents for annual cropping systems.
56. Genetic selection of biological control agents for compatibility with pesticides.
57. Assess the contribution of biological control to IPM systems.
58. Basic understanding of the interactions among components of IPM systems.
59. Genetic engineering to improve the effectiveness of biological control agents in IPM systems.
60. Monitoring systems for biological control agents.
61. Storage, transportation, and quality control of/for released or applied biological control agents.
62. Acquisition of basic information to attract industrial development of biological control (production, formulation, etc.).
63. Development of systems models to be used as integrative tools.
64. Methodology to incorporate mortality due to biological control agents into action thresholds.
65. Develop more effective strains and/or biotypes.
66. Effect of biological control agents on registration of other IPM tactics.
67. Population dynamics of components of the agroecosystem.
68. Technology transfer through applied cooperative research.
69. Development of effective application technology.
70. Research on allelopathy and integration into IPM.
71. Host and biological control agent dispersal and colonization.
72. Biological control of migratory pests in the source reservoir site.
73. Interorganismal genetics.
74. Dispersal of microbial agents under natural and induced conditions.

APPENDIX F

BIOLOGICAL CONTROL AND ECONOMIC THRESHOLDS

Research Needs to Further Threshold-Based Management
Programs That Incorporate Biocontrols

1. Develop simple predictive tools for making field decisions.
2. Establish economic thresholds for target and ecosystem, including theoretical basis for thresholds and biocontrols.
3. Short and long term forecasts of populations in annual and perennial crops.
4. Determine the impact of biotic agents on target organisms.
5. Sampling and monitoring procedures for simple and accurate predictions, including rapid methods for implementation programs.
6. Determine influence of environmental and host-plant effects on thresholds.
7. Survey and identify biotic agents.
8. Forecasting management system events (long term).
9. Effects of abiotic factors on biocontrol agents.
10. Develop epidemiological models.
11. Develop monitoring/sampling techniques to assess biocontrol agent density and impact on target.
12. Economic risk analysis in decision making (including yield variability and models for relating costs and returns for biocontrols).
13. Effects of chemical control on natural biocontrol agents (non-target).
14. Ecological interactions between biotic factors (predator-prey-host: plant or animal).
15. Develop models linking pest activity, crop losses, and thresholds.
16. Determine risks associated with biocontrol thresholds.
17. Economic evaluation of biocontrol programs versus other control programs.
18. Importance of agronomic practices on biological control and on thresholds.
19. Develop methods for the rapid assessment of damage-loss relationships; define biology of damage-loss relationships.
20. Long term studies to predict probabilities of occurrence and abundance of target species and biocontrol agents, movement of potential biocontrol agents, and movement of targets.
21. Develop technology for effective application of beneficials and minimum thresholds for natural enemy releases.
22. Determine the benefits of thresholds, if thresholds can be managed, and long term vs. short term value—dynamics.
23. Economic effects of IPM programs.
24. Evaluate biocontrol agents for regulation potential.
25. Develop standardized protocols for sampling.
26. Economic and ecological benefits of chemical non-use to the environment.
27. Determine weed thresholds with respect to timing of competition.
28. Develop models to predict field results based on laboratory systems.
29. Readily available control backups.
30. Market dynamics as they influence use of biological control.
31. Determine application of thresholds to qualitative observations.
32. Genetic changes in efficacy of biocontrol agents.
33. Effects of PIK or other political/social programs on threshold-based management programs.

APPENDIX G

QUARANTINE TECHNOLOGY

Ideas for Improving the Quarantine Process

1. Develop or refine protocols whereby a candidate species is safe to introduce to the target area.
2. Increase support for taxonomy and biosystematics.
3. Improve communication between researchers and port-of-entry officials.
4. Screen for host range in the country of origin before importation.
5. Develop artificial tests for quarantine use.
6. Use and create quarantine facilities in areas where escape poses no problems.
7. Standardize federal and state regulations.
8. Increase research on quality control.
9. Expand quarantine facilities and people.
10. Develop a centralized information system.
11. Have taxonomists available at the time of shipment.
12. Garner multi-institutional support for quarantine programs.
13. Improve methods for detecting and preventing escape.
14. Improve personnel training.
15. Better educate scientists in the handling and sending of biological control agents.
16. Develop a protocol for possible escapes.
17. Refine methods to get organisms from port-of-entry to quarantine.
18. Increase screening of agents in quarantine.
19. Standardize practical design criteria.
20. Use pest controls in quarantine.
21. Develop computer facilities for quarantine procedures.
22. Improve communication among quarantine facilities.
23. Develop protocols for non-specific biological control organisms.
24. Determine the disposition of pathogens.
25. Develop criteria for handling unsolicited materials.
26. Determine disposition of shipment residue.
27. Improve the manipulation of target and beneficial organisms in breaking diapause.
28. Develop ways to store biotic agents.
29. Improve relations with foreign scientists in biocontrol.
30. Hold periodic workshops to discuss quarantine procedures and techniques.

APPENDIX H-1

FOREIGN EXPLORATION

Areas of Need and Technology Input

1. Determine pest and beneficial insect biotypes.
   a) Electrophoretic analysis of pest populations.
   b) Biochemical studies: isozyme, comparative bioassays in entomopathogen insects.
   c) Develop central lead labs in the U.S. where type material can be sent for identification using biochemical, etc., means for determination.
   d) Karyotype research, protein analysis, isozymes.
   e) Agglutination studies.
   f) Cooperation between laboratories on characterization and screening of biotypes—each laboratory handling a particular phase of the process (e.g., one lab will specialize in isozyme analyses, another in bioassay procedures for particular organisms).
   g) Increase taxonomic studies and techniques; relate techniques (for example, isozyme analysis) to field situations and applications.
   h) Implement research programs using all available tools (morphological, taxonomic, genetic, ecological, biochemical, etc.) to determine biotypes.
2. Diverse acquisition sites.
   a) Electrophoretic typing of pest populations in foreign and domestic areas.
   b) Basic museum and literature searching.
   c) Improved biosystematic studies in disciplines.
   d) Compilation of native insects in hosts (i.e., need for more taxonomic centers in various countries and/or control computer bases).
3. Determine center of origin.
   a) Work more closely with paleobotanists, ancient pollen records.
   b) Support systematists for phylogenetic and historical biogeographic studies that will point out probable centers of origin.
   c) Use taxonomic findings to develop a better understanding of geographical distribution of target and agent species (and subspecies).
   d) In countries where a pest species is present, know the history of that pest in the country or the history of the crop; compiling this information for as many countries as possible will make it easier to locate promising collection locations.
4. Develop multidisciplinary research teams.
   a) Send a central newsletter to any interested party listing planned trips; the USDA might administer such a list; inclusion is voluntary.
   b) Requires liaison and communication.
   c) Principally a problem of administrative support.
   d) Establish a "pool" of qualified explorers from which to draw.
   e) Through SRDC-82-11, and other groups, provide opportunity for interdisciplinary participation. Do not keep money and opportunities in the hands of a few people.
   f) Better identification of targets and areas of origin; better communication between scientists and/or means of identifying scientists planning foreign travel.
   g) Multidisciplinary laboratory biocontrol.
   h) Train foreign explorers in plant pathology, entomology, nematology, and insect pathology.
5. Conduct minimal ecological studies in area of origin.
   a) Requires financial support and facilities to spend at least several weeks during pest season in foreign countries.

b) Ecologists provide guidelines for normal time-limited studies.
c) Identify ecological situation of target species in this country; use nationals in regions where target species are native.

6. Determine worldwide distribution of natural enemies.
   a) Requires very large-scale project and coordination.
   b) Use and interact much more than in the past with the Western Hemisphere IOBC group. This group, if developed and supported properly, could be most helpful in the above items and could strengthen some of the other items.
7. Select optimal climatic region.
   a) Communicate with APHIS, customs, and shippers about such problems; set up labeling system recognized and accepted by each group; develop packaging for shipping material.
8. Foreign administrative clearances.
   a) USDA emphasis on this through their cooperative science agreements.
   b) Establish government representative liaisons/counterparts among countries; discuss problems and move to solve them.
   c) Establish intergovernment bureaus or personnel in most countries, promoting concept of reciprocation.
   d) Customs limitations can be severe problems, especially because this type of importation and exportation is not specifically addressed and spelled out in customs regulations in any country. They should be. Ideally, a universal customs procedure should be developed internationally.
   e) Through the United Nations, obtain world-wide recognition and sponsorship of biocontrol that would ease administrative problems in countries with restrictions. Keep CIA or similar organizations from infiltrating the field.
   f) Direct government diplomatic efforts toward establishing channels for scientists to use. Help scientists know the rules of cooperation/reciprocation.
9. Natural enemy biotypes.
   a) Electrophoretic typing and correlation with biological traits.
   b) Monoclonal antibody technology may be of use here; matching the lipid profile of the natural enemy with the host or prey may be of use, also.
   c) Karyotype research, protein analysis, and isozymes--all tests to show compatibility (feedings, behavioral, synchrony).
   d) Studies and collections must be as comprehensive as possible over time and geography.
   e) Botanical and chemical means of determining the existence of weed biotypes.
   f) Testing overseas against U.S. target to obtain information on biological effectiveness, etc.; collect from different zones and test for host range; use to obtain control over wider area and under more diverse environmental conditions.
10. Computer data base for natural enemies in given crop systems.
11. Funding sources.
12. Adequate quarantine facilities.
13. Foreign search strategies.
    a) For row crop insect pests, searches should coincide with development stages of crop, include a diverse number of habitats (e.g., fields), and be conducted over the longest period of time.
    b) Computer information based on experience of people who have already been in potentially "good" search areas.
    c) Related host genera should be assured for natural enemies while attached to the target host.
    d) Improve collection of maximum diversity in genetic material; include all natural enemies in the host samples.
    e) Often, the problem is just finding natural enemies--send as many as are found.
    f) Sponsor a symposium of ecologists, samplers, and experienced and potential explorers; publish results.

g) Dependent on country, target species—get down and look.

14. Host country cooperation.
    a) Improve through ethical standards of foreign explorers, reciprocity with material and information, respect for local institutions and culture.
    b) Information and scientist exchange.
    c) Publish exploration findings in search countries; exchange materials (biological control agents).
    d) List labs and personnel in the U.S. willing to cooperate with other countries' exploration teams; distribute in spirit of cooperation.
15. Technical support staff in area of search throughout the seasons.
    a) Through funds, i.e., AID funds, or funds that must be spent in a particular country.
    b) Work through retired university people or students at universities in country of search.
    c) Administer support as needed; if foreign exploration has priority, this could be done.
    d) Use the technical support of a collaborator in the country of the search—a less expensive way to ensure technical support.
    e) Make ways available through diplomatic channels for long tours; arrange technical and physical support for stays; establish labs (like Rome Weed Lab) throughout the world.
    f) A funding problem; frequently not necessary or important.
16. Preliminary screening facilities in search area.
17. Mechanisms for rapid shipment.
    a) Mechanical aspects, procedures available.
    b) Administrative problem: requires additional regulations or protocol coming from top.
    c) USDA/APHIS inspectors should handle clearance of shipments and transshipment (inspector involved in introduction).
    d) Not easily solvable; can be eased by improving communication between researcher and customs or PPQ officers (get to know your customs/PPQ officials first-hand).
18. Problems of access to politically sensitive areas.
19. Intergovernmental biocontrol network.
20. Population genetics of introduced species.
    a) Get the right person; geneticists not usually interested in practical questions; entomologists afraid of theoretical genetics; ideal person probably a hybrid.
    b) Especially determine whether it is theoretically more appropriate to release all collected individuals or to do some genetic preselection before release, considering that mating will not be completely random.
21. Minimum sample size from one area at one specific time of season.
22. Coordinate exploring groups.
23. Choice of natural enemy biotype.
24. Administrative recognition of needed support for foreign exploration.
    a) For foreign non-researchable work.
    b) Greater publicity of biocontrol success (national TV coverage, national newspapers, and magazines); administrators often respond to public pressure rather than their scientific staff.
    c) Contact with senators and representatives; groundswell support from farmer groups.
    d) USDA/APHIS-U.S. Customs must be pressured into interacting.
    e) Foreign searches should be exempt from travel freezes, restrictions, etc.—as long as within budgets.
25. Shipment techniques.
26. Control computer data base for all phases related to biological control.

a) Country-by-country or regional computer-based (remote terminal accessible) directory of foreign agencies and/or individuals; directory of agencies who may or may not be helpful but whose approval or cooperation is essential.
b) Central lab to store all biocontrol information on a computer; others can contribute to data base with proper credit given to each contributor (this is important for verification problems).

27. Importance of complementary natural enemy components.
28. Prioritized list of biocontrol targets.
29. Field assessment of control value of biological agents.
    a) USDA should buy, outfit, and make available mobile labs for individual biocontrol researchers.
    b) Conduct incidence studies in foreign fields.
    c) Through direct observation and using host eggs and larvae (pinned to cards) assess predation and parasitization processes.
30. Search in areas of low host density.
31. Reciprocal exchange of materials and information.
32. Feedback from previous introductions.
33. Evaluate species complexes in country of origin.
    a) Foreign students to conduct directed studies under U.S. foreign faculty cooperative direction.
    b) Faunistic surveys of crops, including non-crop components within the field and in the margins.
34. Flexibility in U.S. importation permits.
35. Simplified host range screening.
36. Minimum numbers needed for establishment.
37. Unified customs procedures.
38. Community ecology studies as a basis for foreign exploration.
39. Searching ecologically homologous areas.
    a) Investigate value of climate matching: is it best to match climates or match developmental thresholds?
    b) Identify similar but geographically distant ecosystems that share similar crop systems but with different management and pest intensities.
    c) Emergence intervals/degree days matches or purposeful selection of disparate developmental times.
40. Ethical standards in foreign exploration.

APPENDIX I-1

INCREASING THE ABUNDANCE AND EFFECTIVENESS OF BIOLOGICAL CONTROL AGENTS

Chemical and Nutritional Manipulations

Chemical Manipulations

1. Pesticide interactions.
2. Developing encapsulating material for timed release.
3. Influence of pH effects.
4. Conservation tillage in reducing pathogen load.
5. Treating plants to effect exudates; management of exudates.
6. Use of fumigants or other chemicals for competition.
7. Genetic selection of biotic agents in anticipation of environmental stresses.
8. Formulation for protection from environment.
9. Role of secondary plant compounds on host selection and/or suitability.
10. Kairomone and non-kairomone attractants in host-plants that trigger orientation by natural enemies or antagonists.

Nutrient Manipulations

1. Deciphering limiting nutritional factors.
2. Nutritional amendments.
3. Breeding plants to affect exudates; management of exudates.
4. Nutritional requirements for successful infection or natural enemy development.
5. Nutrition requirements for successful infection/natural enemy development.
6. Alternate hosts/plants—effects.
7. Combinations of biota/nutritional interactions.
8. Site specific nutritional differences for microbial antagonists for strategic placement.
9. Effects of crop bloom period on effectiveness of parasitoids/predators.
10. Artificial media for rearing parasitoids/predators.

Combined Chemical and Nutritional Manipulations

1. Soil amendments for enhancing indigenous antagonists.
2. Cultivar-antagonist interactions.
3. Soil fungistasis.
4. Formulation to enhance activity.
5. Attractants (kairomone) added to predator food sprays to increase oviposition prior to prey outbreak.
6. Effect of additive on non-target species.
7. Identification of basic flora in microenvironment.
8. Eliminate competition to ensure establishment.

APPENDIX I-2

INCREASING THE ABUNDANCE AND EFFECTIVENESS OF BIOLOGICAL CONTROL AGENTS

Physical Manipulations

1. Surface charges.
2. Particle size/surface area.
3. Soil compaction.
4. Soil drainage/moisture.
5. Limiting optimal environmental factors affecting potential for establishment.
6. Soil treatment.
7. Soil tillage.
8. Crop-residue management.
9. Ancillary effects of amendments.
10. Seedbed management.
11. Genetic selection of agent for physical factor tolerance.
12. Timing and type of irrigation.
13. Habitat color modification.
14. Fallowing practices.
15. Soil texture/type.
16. Anerobiosis.
17. Plant surface morphology.
18. Photoperiod effect.
19. Field shelters.
20. Cultural practices.

APPENDIX I-3

INCREASING THE ABUNDANCE AND EFFECTIVENESS OF BIOCONTROL AGENTS

Vegetation and Cultural Management

1. Knowledge of plant and animal components present in the system.
2. Microenvironmental manipulation: how it is done, and its effects.
3. Effect of no-tillage agriculture on biological control agents.
4. Knowledge of microenvironmental requirements of biological agents.
5. Effects of crop and non-crop vegetation management techniques (i.e., fire, reseeding, fertilization) on biocontrol agent effectiveness in rangelands.
6. Knowledge and improvement of overwintering sites.
7. Effect of crop plant on the establishment, persistence, and maintenance of biological control agents (include specific choice of varieties).
8. Effects of alternate host plants of the pest on the beneficial agents.
9. Introducing new plants to a crop system as associated plants, roadsides, windbreaks, etc.
10. Study existing natural and managed ecosystems where biocontrol operates.
11. Study biology, behavior of biocontrol agents, and effects of ecological factors on activity of biocontrol agents.
12. Determine conflicting and synergistic effects of cultural management techniques (i.e., a technique that enhances an insect natural enemy but also increases a plant disease).
13. Determine nutritional requirements of biocontrol agents.
14. Determine effects of community structure in time and space on pests and associated natural enemies.
15. Determine cultural practices (fertilization, plant configuration, thinning, pruning, etc.) to reduce host pest densities to a level that can be handled by natural enemies; lower pest densities to low levels for predators to be effective.
16. Predispose pest host through chemical, cultural, and biological means to favor biocontrol agents; includes making conditions less favorable to pest.
17. Adding nutrient base (adjustment) to enhance antagonists.
18. Define ecological needs for imported biocontrol agents.
19. Timely destruction of alternate host plants to force movement of biocontrol agents (reservoir management) into target areas.
20. Determining socio-economic benefits of manipulations.
21. Determine sources and movement of biocontrol agents.
22. Understand ecological requirements of plant components to be manipulated.
23. Long term effect of crop rotations on biocontrol.
24. Effects of manipulations to the total farming system on the biocontrol organisms in particular subsystems of the farm.
25. Study negative biotic and abiotic factors affecting biocontrol agents (hyperparasites, general predators, etc.).
26. Identify plant and animal components; determine trophic interactions between components.

APPENDIX I-4

INCREASING THE ABUNDANCE AND EFFECTIVENESS OF BIOCONTROL AGENTS

Propagation and Release

1. Selection of pesticide resistance (electrophoresis).
2. Precision in identifying biotypes (pest and biological agent).
3. Genetic improvement for enhanced resistance to environmental stresses.
4. Diapause manipulation.
5. Timing of release.
6. Nutritional requirements to improve vigor and fecundity.
7. Genetic improvement of characteristics of biocontrol agents.
8. Application or release technology.
9. Conditions necessary for producing effective agents *in vitro*, *in vivo*, and *in situ*.
10. Stockpiling, storage, and transportation: insure viability and effectiveness.
11. Propagation and use of obligate parasites.
12. Use artificial hosts to rear bioagents.
13. Increase data on biology of bioagents.
14. Use of heterosis for production of standard strains.
15. Parasite/host release ratios.
16. Industrial cooperation.
17. Effect of environmental and cultural practices on control agent.
18. More precise field evaluation.
19. Involvement of public sector.
20. Manipulation of dormancy.
21. Efficacy data on application and release timing and release rates relative to pest populations.
22. Effects of environment on sex ratios in the lab.
23. Effect of other cultural practices, including pesticides.
24. Bridge gaps between lab, greenhouse, and field.
25. Stockpiling natural enemies for future.
26. Research alluding to ecology of area of application.
27. Fermentation technology.
28. Regional testing.

APPENDIX J

IDEAS GENERATED IN THE MICROBIAL AGENTS WORKSHOP

Research Ideas for Using Microbial Agents in Biological Control

1. Develop new approaches for identifying more efficacious microbial agents.
2. Study the nature of interactions among antagonists.
3. Compare efficacy of single strain versus multiple strains of antagonists.
4. Assess the dependability and appropriateness of field tests for biocontrol.
5. Ascertain the possibility of using root exudates for screening and enhancing the activity of antagonists.
6. Determine optimum age of target and antagonist for infection or susceptibility.
7. Ascertain if test organisms reflect diversity of natural populations.
8. Modify laboratory and greenhouse conditions to mimic field conditions.
9. Design detection methods to select for a particular mode of action by antagonists.
10. Develop methods for selecting antagonists for particular plant parts.
11. Assess the impact of microbial mutation on biocontrol.
12. Exploit microbial mutation for selecting beneficial antagonists.
13. Evaluate the impact of various storage techniques for microbial agents and their products.
14. Improve trait identification, monitoring, and maintenance.
15. Develop procedures to stabilize mutants.
16. Explore natural variability.
17. Study parasitic fitness.
18. Study field genetic transfer.
19. Determine substrate effect on efficacy of antagonist.
20. Develop quality assurance procedures by standardizing units, developing reproducible field bioassays and sampling procedures, and developing thresholds for microbial contamination.
21. Study interactions of antagonists and targets.
22. Determine optimum age of targets to insure maximum efficacy.
23. Determine the effect of stress on targets.
24. Determine the effect of plant modification on microbial agents.
25. Determine the effect of incompatible agents (insecticide, herbicides, etc.) and timing of their application on microbial agents.
26. Study the effect of carrier equipment on the activity of microbial agents.
27. Study the effect of crop on the activity of microbial agents.
28. Determine appropriate timing of application of antagonists.
29. Assess the effect of the environment on antagonism.
30. Determine antagonist durability at the target site.
31. Determine differences in target susceptibility in the field and laboratory.
32. Determine the effects of environmental factors on enzymes and metabolites of antagonists.
33. Develop common terminology.
34. Develop simulation modeling for microbial activities.

APPENDIX K-1

BIORATIONAL PESTICIDES PERFORMANCE DATA REQUIREMENTS*

Necessary Test Details

1. Efficacy.
   a) Identity of pest, its prevalence and level of control compared to untreated plots and the commercial standard.
   b) Time required after application to achieve desired level of control.
   c) Minimum effective dosage required to achieve desired level of control.
2. Available Information on Host Spectrum (Nontarget organism hazard data).
3. Crop Phytotoxicity Data - Type, amount and duration. (Explain fully; was it commercially acceptable. Phytotoxicity data should be recorded for the maximum use rate and 2 to 4X the maximum use rate. Make several ratings; e.g. early, mid and late season etc., if appropriate.)
4. Rating Scale Explanation should be clear for all efficacy and phytotoxicity ratings.
5. Crop Yields - Where appropriate, yield data should be taken for treated and untreated plots to verify usefulness of the product. Qualitative and quantitative data are recommended.
6. Appropriate Statistical Treatment of Results, include all raw data.
7. Product and Formulation Tested, lot number, etc.
8. Crop Variety.
9. Soil Type, Soil pH and % organic matter if soil application.
10. Location - State, county, and nearest town.
11. Plot Size and Number of Replications.
12. Planting Date or Tree Age.
13. Dosage Rate and Dilution Rate e.g., lbs. active ingredient (a.i.) per acre. If banded, list band width and row spacing of crop, and ozs. a.i./1000 linear feet of row. Also list spray volume per acre.
14. Application Date(s) and Method - Be specific as to how applied, e.g., directed spray to base of plant.
15. Application Equipment (Type, nozzle size, pressure, etc.).
16. Timing of Application.
    a) Growth stage of crop.
    b) Pest stage of growth (e.g. weed growth stage for weed control treatment).
17. Other Pesticides Applied and dates of application.
18. Interval between treatment and planting, emergence, or harvest as appropriate.
19 Rating Dates and Harvest Dates.
20. Environmental Conditions - Local temperature and precipitation and or irrigation information from the first application to end of test period.
21. Pertinent comments regarding unusual test conditions, which might influence results.

*EPA has waived all requirements to submit efficacy data except those dealing with public health areas. The Agency reserves the right to require, on a case-by-case basis, submission of efficacy data for any pesticide product registered or proposed for registration.

BIORATIONAL PESTICIDES NON-TARGET ORGANISM AND ENVIRONMENTAL FATE DATA REQUIREMENTS

	TEST SUBSTANCE	REQUIRED FOR BIOCHEMICALS	REQUIRED FOR MICROBIALS	NOTES
TIER I:				
Avian Acute Oral 1)	Technical 2)	X	X	
Avian Dietary 1)	Technical	X		
Avian Injection Test 1)	Technical		X	
Wild Mammal Injection Test 1)	Technical		X	Required if toxicology data are inadequate or inappropriate to assess hazards
Fresh Water Fish Test 1)	Technical	X	X	
Fresh Water Invertebrate Testing 1)	Technical	X	X	
Estuarine and Marine Animal Testing 1)	Technical		X	Required if applied directly into estuarine or marine enviro-ments or expected to enter because of use pattern
Plant Studies	Technical (Biochemicals) end use product (Microbials)	X	X	Required if there is a phytotoxicity problem and open literature data are not available; or there is a hazard to endangered species.
Nontarget Insect Testing	Technical	X	X	Required on a case-by-case basis depending on mode of action
Honeybee Testing	Technical		X	

TIER II, III, AND IV Tests are conditionally required and requirement depends upon Tier I studies and availability of adequate toxicology data. Data requirements are listed below:

TIER II - BIOCHEMICALS - volatility, dispenser-water leaching, adsorption-desorption, octanol/water partition, UV absorption, hydrolysis, aerobic soil metabolism, aerobic aquatic metabolism, soil photolysis, aquatic photolysis

- MICROBIALS - terrestrial environmental testing, freshwater environmental testing, estuarine or marine environmental testing

TIER III - BIOCHEMICALS - terrestrial wildlife testing, aquatic animal testing, plant studies, nontarget insect testing

- MICROBIALS - terrestrial wildlife and aquatic organism testing, avian pathogenicity/reproduction test, definitive aquatic animal tests, aquatic embryo larvae and life cycle studies, aquatic ecosystem test, plant studies

TIER IV - MICROBIALS - simulated and actual field tests (birds, mammal, aquatic organisms)

1) Might not be required if use is limited to greenhouse or indoors (case-by-case basis)

2) Technical = active ingredient prior to formulating

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BIORATIONAL PESTICIDES - TOXICOLOGY DATA REQUIREMENTS

	TEST SUBSTANCE	REQUIRED FOR BIOCHEMICALS	REQUIRED FOR MICROBIALS	NOTES
TIER I:				
Acute Oral	Technical Manufacturing-use product Formulation	R (Required) R R	R R R	Not required for biochemical if test material is highly volatile.
Acute Dermal	Technical Manufacturing-use product Formulation	R R R	R R R	Not required for biochemical if test material is highly volatile. Also not required if test material has pH <2 or >11.5
Acute Inhalation	Technical Manufacturing-use product Formulation	R R R	R R R	Not required for biochemical if test material has simular pH range as above. Required for microbial if 20% or more of the aerodynamic equivalent of the formulation is composed of particulates <10 microns in diameter.
Primary Eye Irritation	Manufacturing-use product Formulation	R R	R R	Not required of biochemicals if test material is highly volatile or pH is <2 or >11.5
Primary Dermal Irritation	Manufacturing-use product Formulation	R R	R R	Required for biochemicals if repeated contact with human skin results under condition of use.
Hypersensitivity Study	Manufacturing-use product Formulation	CR (Cond. Req.) CR	R R	Required for biochemicals if repeated contact with human skin results under condition of use. Required for microbials if use results in repeated human contact by inhalation or dermal route.
Hypersensitivity Incidents		CR	CR	Incidents must be reported.
Genotoxicity	Technical	CR	--	Required if significant human exposure or material is chemically related to a known mutagen.
Cellular Immune Response	Technical	R	R	
Intravenous (IV) Injection	Technical	--	R-bacteria R-virus	
Intracerebral (IC) Injection	Technical	--	R-protozoa R-virus	
Intraperitoneal (IP) Injection	Technical	--	R-protozoa R-fungus	
Tissue Culture	Technical	--	R-virus	

TIER II, and III Tests are conditionally required and requirement depends upon Tier I studies. Some tests may be repeated, depending on the substances toxicity in the original tests. Data requirements are listed below:

TIER II - BIOCHEMICALS - mammalian mutagenicity tests, subchronic oral, dermal and inhalation, teratogenicity, cellular immune response.

- MICROBIALS - acute oral, and inhalation, subchronic oral, acute IP + IC, primary dermal, primary eye, cellular immune response, teratogenicity, virulence enhancement, mammalian mutagenicity.

TIER III- BIOCHEMICALS - chronic feeding, oncogenicity

- MICROBIALS - chronic feeding, oncogenicity, mutagenicity, teratogenicity.

COST AND DURATION OF TIER I TOXICOLOGY STUDIES

The following are estimated costs and approximate durations of TIER I toxicology testing:

Type Test	Cost ($) For Biochemical	Cost ($) For Microbial	Duration of Test
Acutes (oral, dermal & inhalation)	45,000	45,000	14-21 days
Primary irritation(eye & dermal)	5,000	5,000	3 days-skin 7 days-eyes
Hypersentivity study	6,000	6,000	38 days
Genotoxicity	5,000	-----	2-3 days
Cellular immune response	5,000	5,000	14-21 days
IV	------	20,000	14 days
IC	------	20,000	14 days
IP	------	20,000	14 days
Tissue culture	------	20,000	45 days
TOTALS	66,000	141,000	

NOTE: Costs will vary throughout the industry. The above figures represent an upper range estimation if all the tests were required in TIER I.

APPENDIX K-3

INTERIM GUIDELINES FOR ACCEPTANCE OF A BIORATIONAL MATERIAL FOR AN IR-4 PROJECT

1. Production methods are available or potentially feasible to assure commercial availability of the product.
2. Active ingredient has been formulated for practical (field) use and formulation has potential for registration.
3. Appropriate application technology for the formulation exists.
4. Formulation has a defined shelf life.
5. Data is available to demonstrate utility and efficacy. If large scale field studies are not available then:
   a. Biochemical - Use pattern is similar to another of proven value.
   b. Microbial - Preliminary practical scale studies must demonstrate efficacy.
6. Registrant is available or potentially available to accept IR-4 data and register product.
7. Support by IR-4 for registration will be limited to EPA Tier I studies under subpart M and efficacy data.
8. Need for use has been defined and potential exists for commercial use.
9. Efficacy would be competitive with current control practices and selective for target pest.
10. Use would be compatible with current control methods or would replace a current method with no adverse impact on other pest control strategies.
11. Need is in the general public interest and private industry lacks sufficient incentive to obtain data.
12. The product is registerable under EPA policy.
13. There is a need for registration under FIFRA.